Title: Did Dark Matter Annihilations Reionize the Universe?

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Abstract: TBA

Did Dark Matter Annihilations Reionize The Universe?

(Based on recent work with Alexander Belikov, arXiv:0904.1210)

Dan Hooper

Fermilab

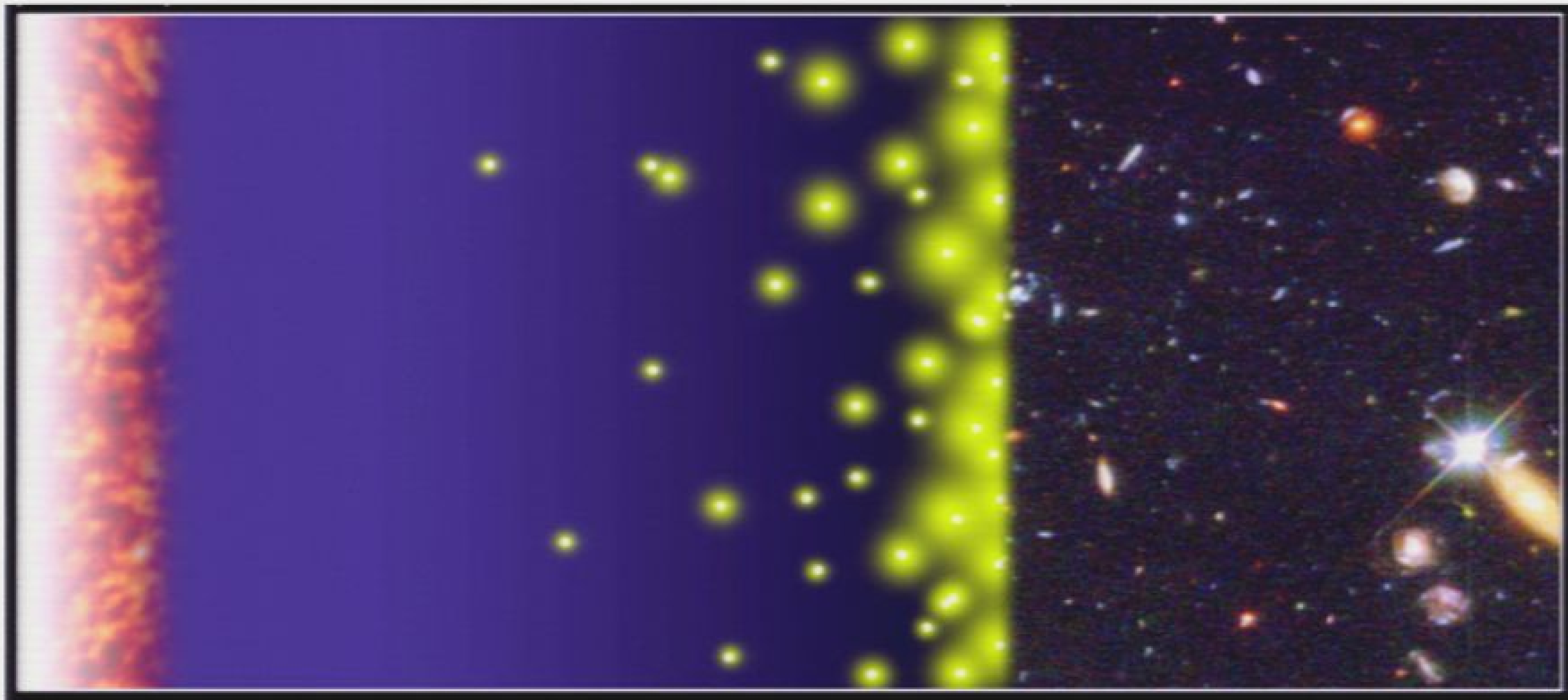
Theoretical Astrophysics Group

New Lights on Dark Matter Conference

Perimeter Institute

June 11, 2009

The Ionization History Of Our Universe



The atoms in our universe have undergone two major phase transitions

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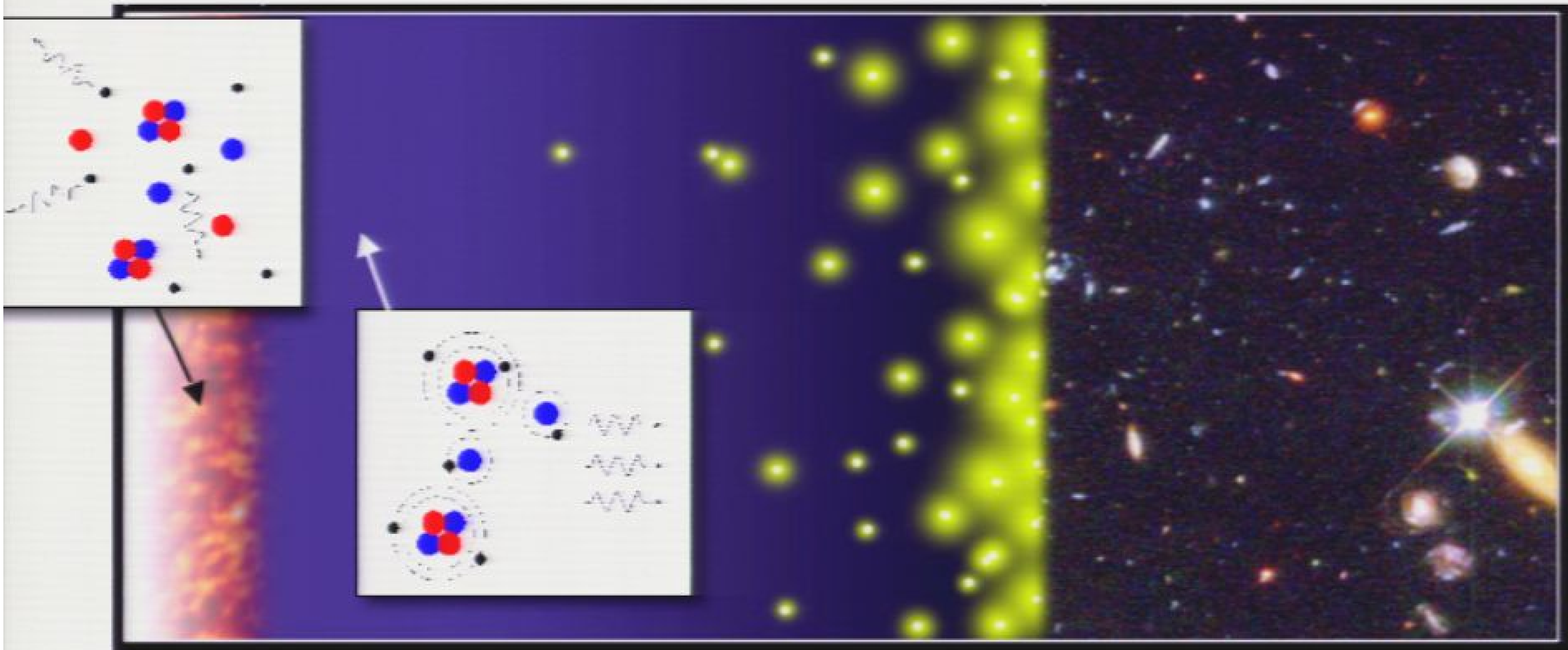
The Ionization History Of Our Universe



1) 370,000 years after the big bang, electrons and protons combine to form neutral atoms, and release the cosmic microwave background

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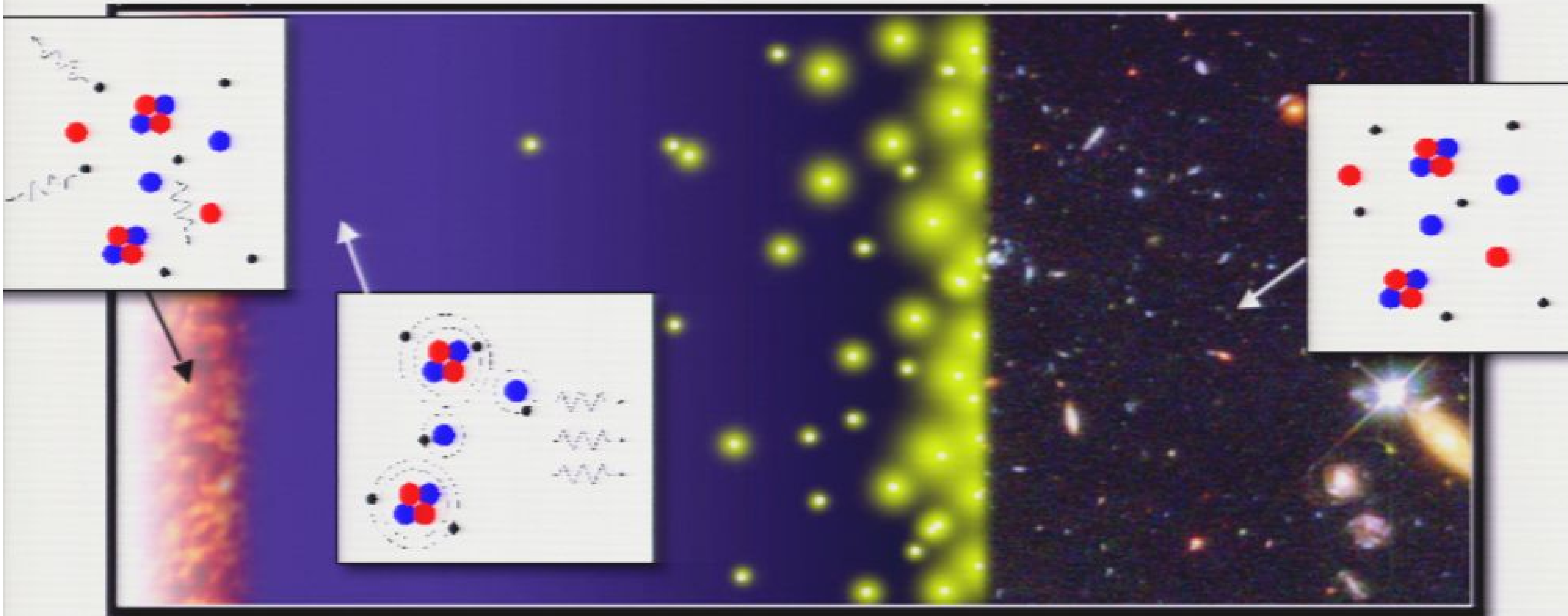


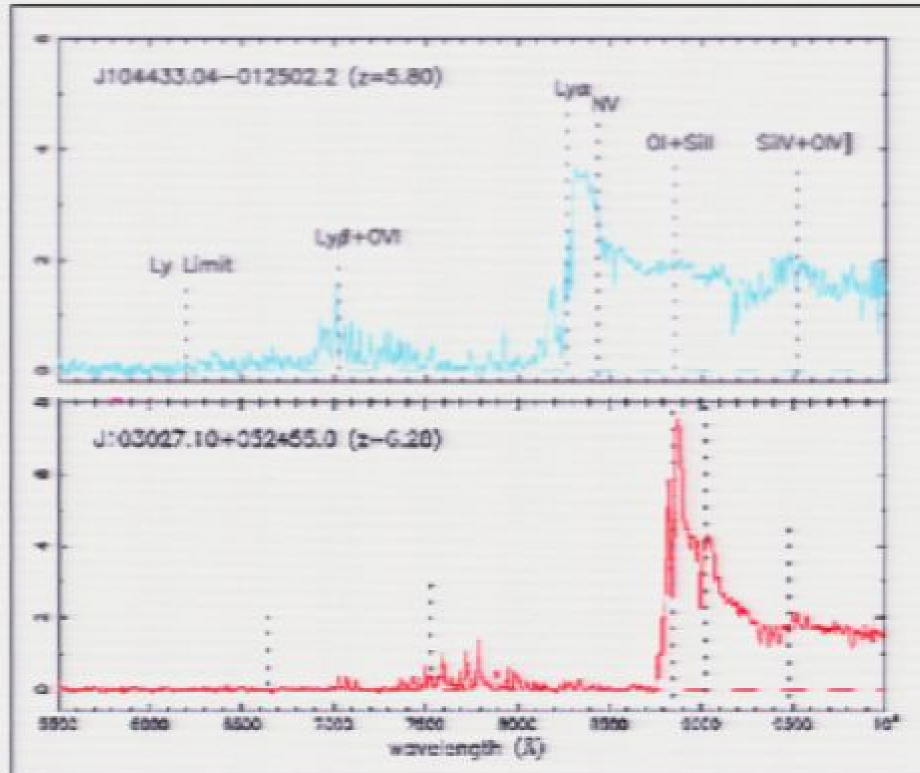
1) 370,000 years after the big bang, electrons and protons combine to form neutral atoms, and release the cosmic microwave background

2) Between z~6-20, our universe's gas once again became ionized

Empirical Handles On Reionization

1) The Gunn-Peterson Trough

- Neutral hydrogen absorbs light very efficiently via the Lyman-alpha transition
- The lack of strong Lyman-alpha absorption in the spectra of very distant quasars demonstrates that the vast majority of hydrogen since z~6 was ionized



2) CMB Anisotropies

- Thompson scattering of the CMB photons with free electrons can produce observable anisotropies
- WMAP has reported a Thompson optical depth of the universe of $\tau=0.087\pm0.017$ (about 0.04 of which corresponds to full ionization at $z<6$)

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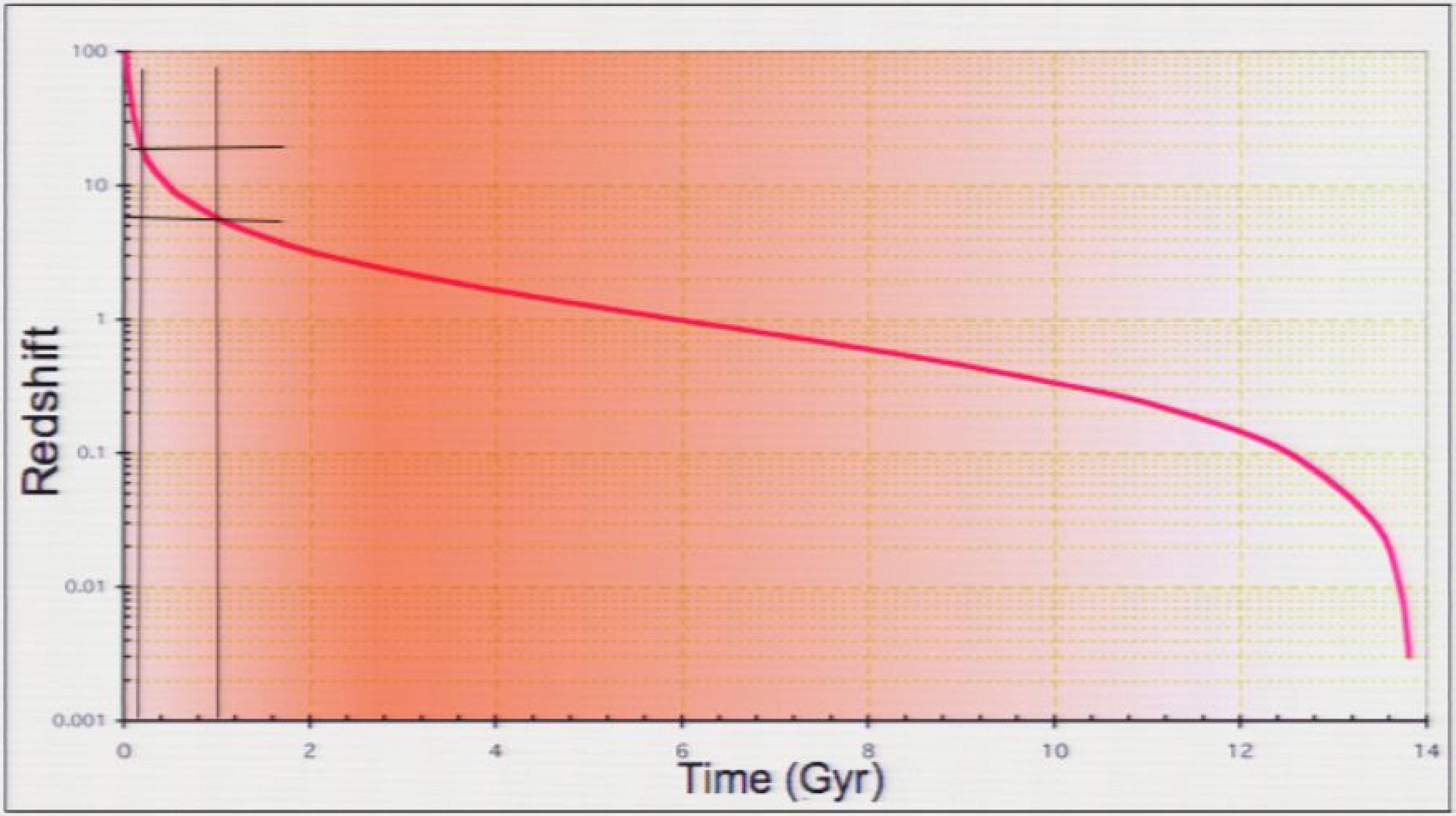
What Caused Reionization?



Redshifts of z~6-20 correspond to ~200 million years to ~1 billion years after the Big Bang - little in the way of sources of ionizing radiation

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What Caused Reionization?

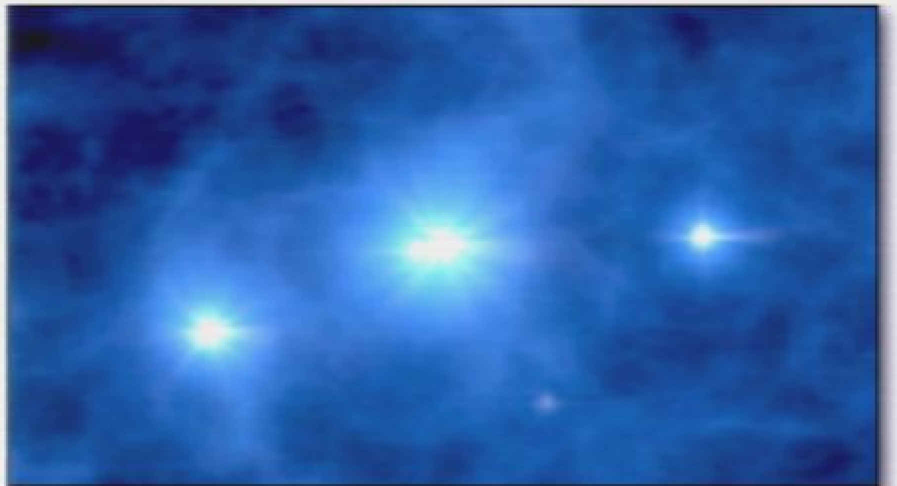
Two leading candidates:

- Early Stars
- Quasars

Conventional* View:

At z > 6, UV radiation from star forming galaxies dominated reionization; at z < 4, non-thermal emission from quasars became significant, enabling the double ionization of helium

(Madau, Haardt, Rees, 1999)



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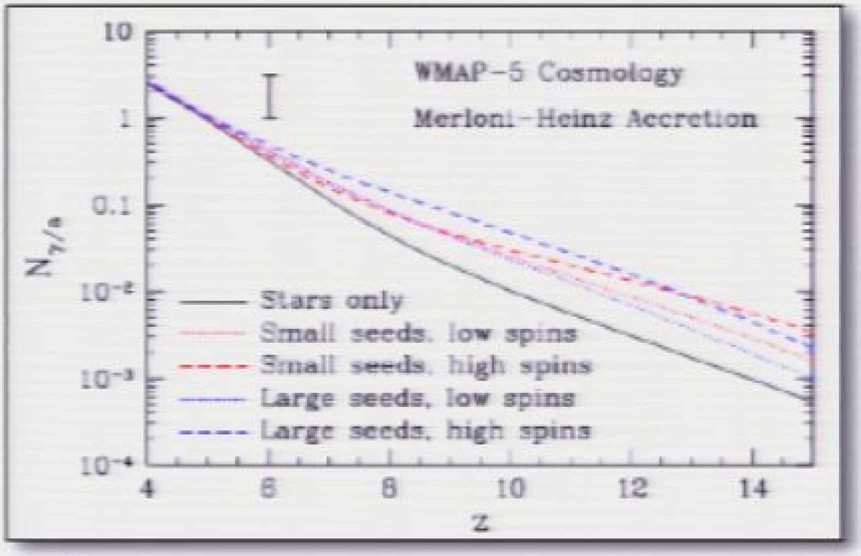
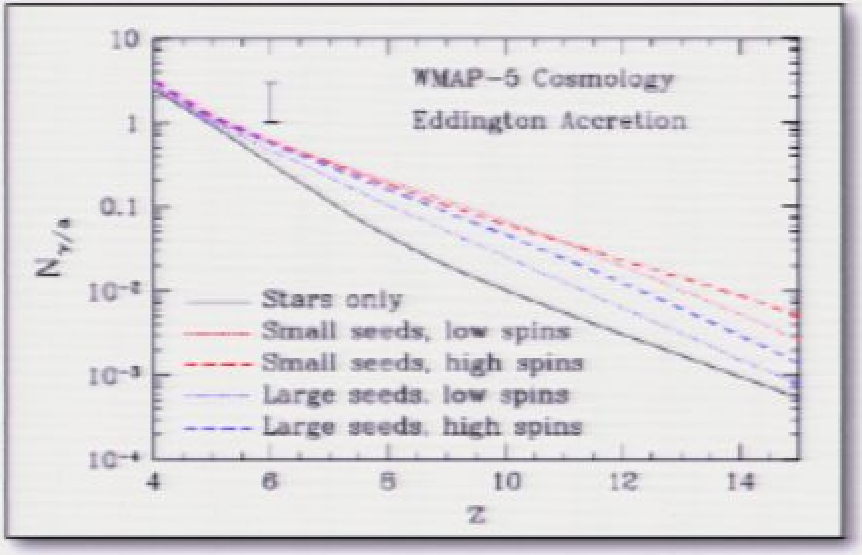
* Not to be confused with "Consensus"

What Caused Reionization?

- The convention scenario, however, does not automatically lead to the full reionization of the universe by z~6





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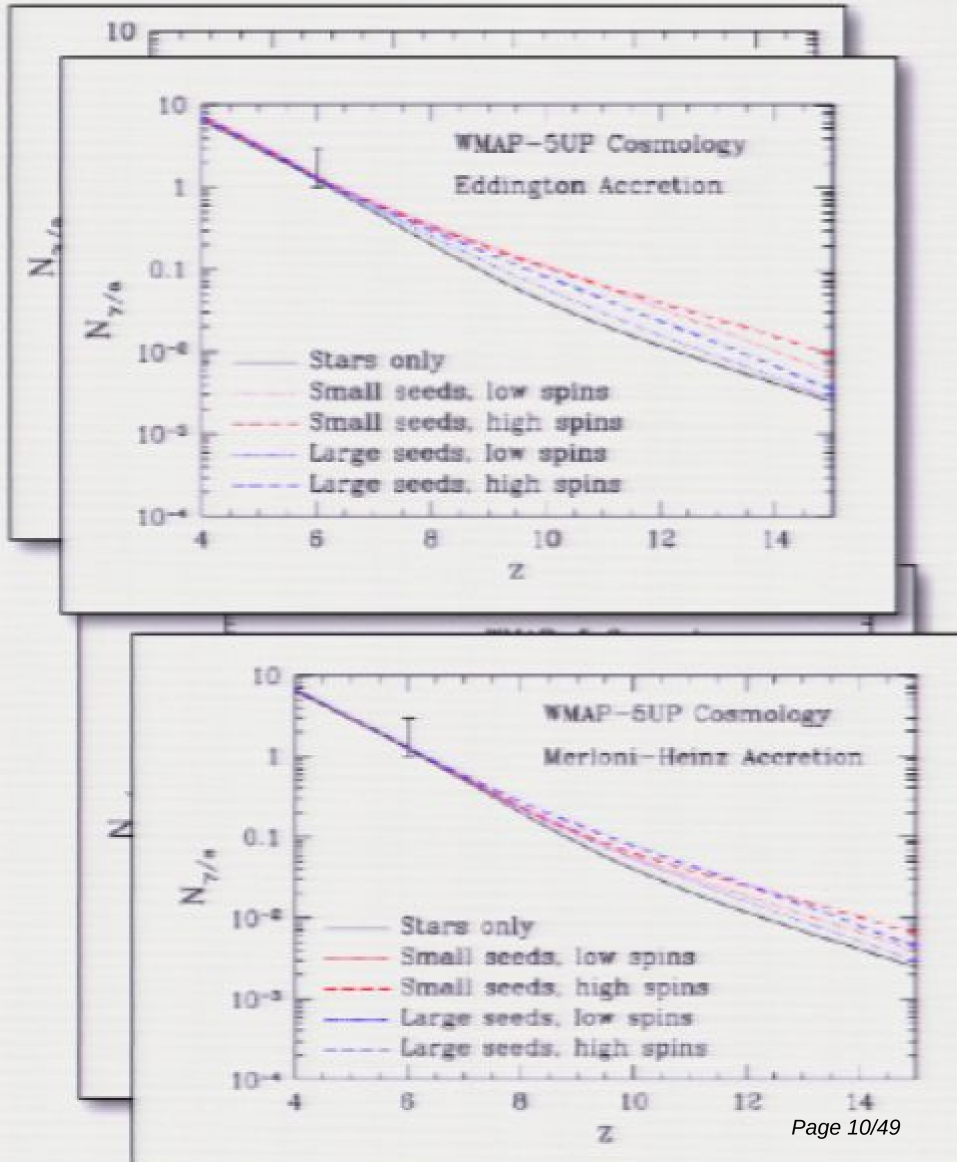
Volonteri and Gnedin, 0905.0144

What Caused Reionization?

- The convention scenario, however, does not automatically lead to the full reionization of the universe by z~6

- This can be accommodated by reasonable (1σ) shifts in cosmological parameters (σ_8, η_s)



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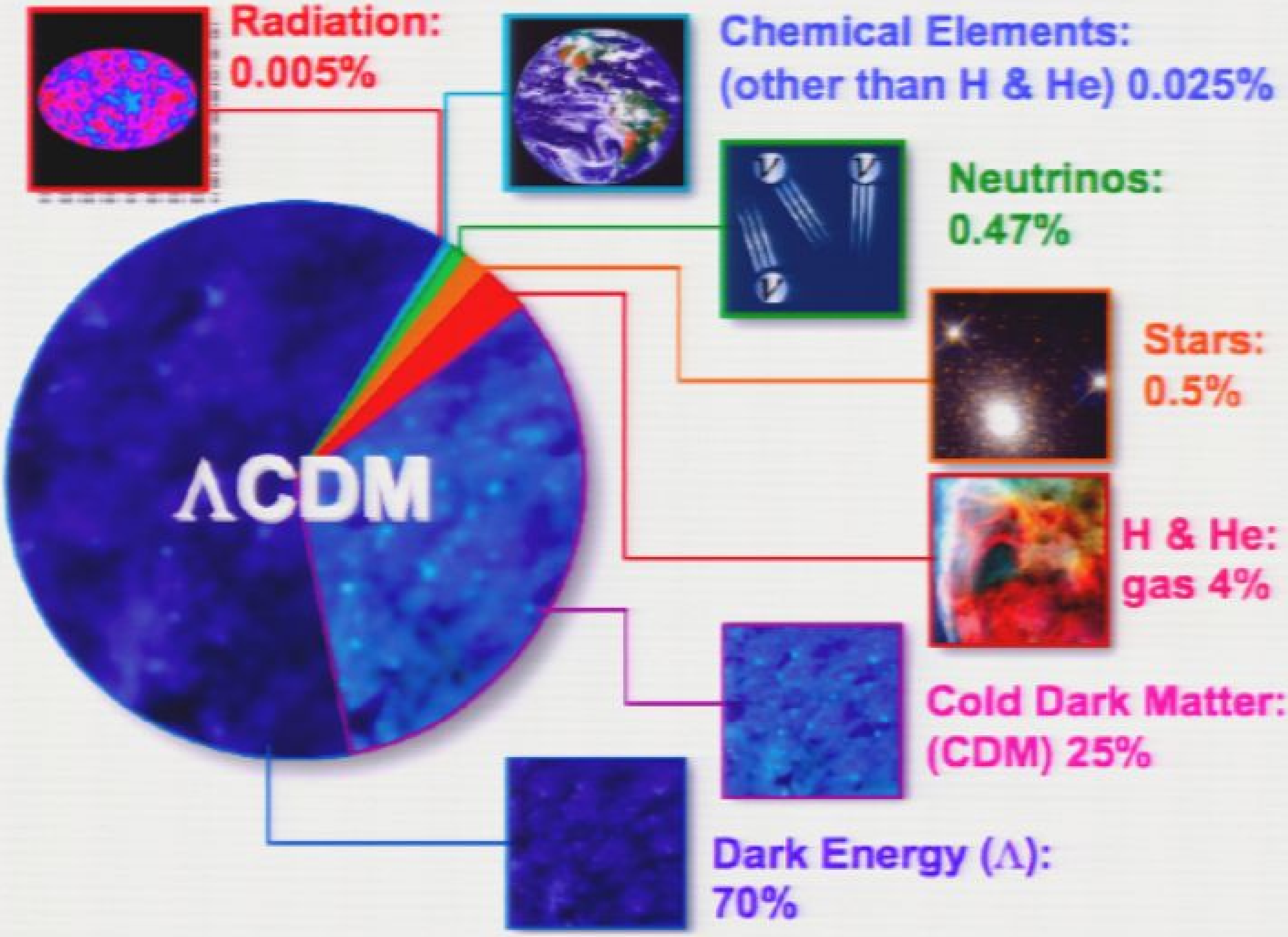
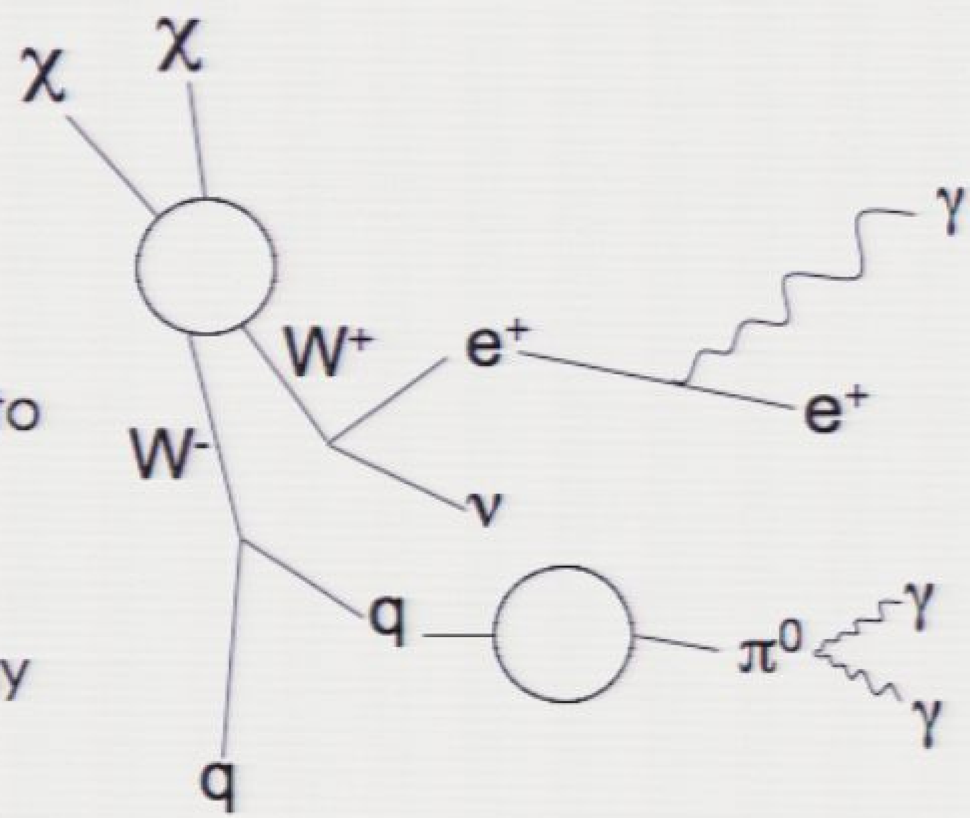
Dark Matter As An Alternative Source Of Ionizing Radiation?



Dark Matter As An Alternative Source Of Ionizing Radiation?

- Over the first billion years, dark matter had begun to form clumps and annihilate efficiently
- Dark matter annihilation products include gamma rays, which can scatter with electrons, causing gas to become ionized
- If one in ~10^9 dark matter particles annihilate during this era, the energy released would be sufficient to completely reionize the universe



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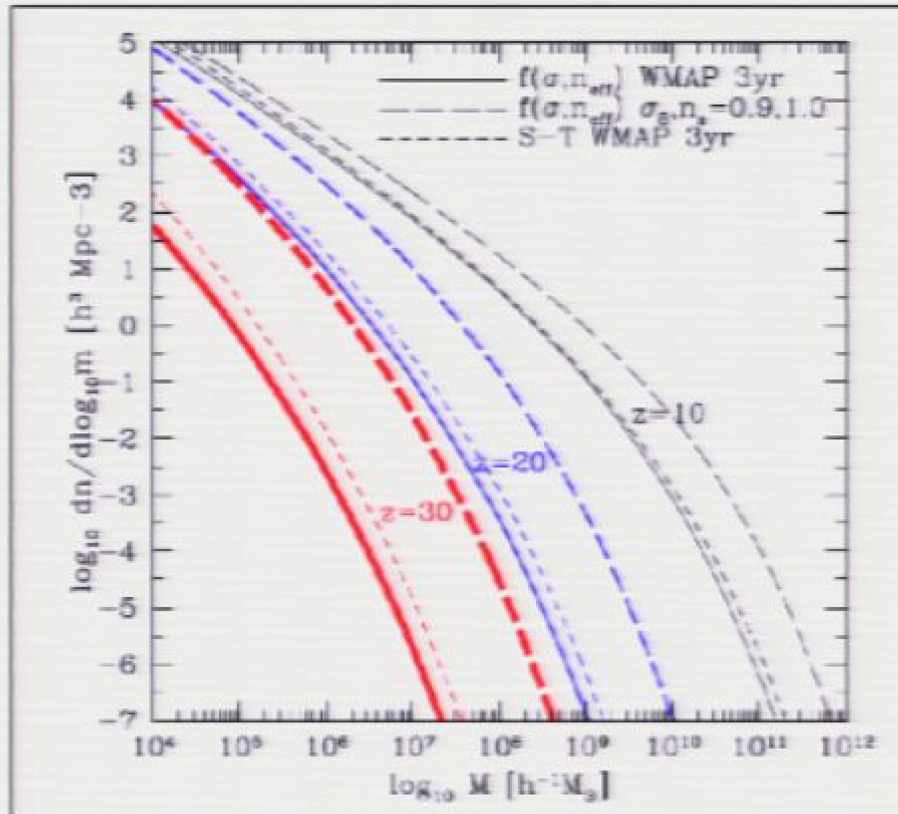
Dark Matter Halos At z~6-60

- N-Body simulations indicate that the first (and smallest) clumps of dark matter formed by z~60
- Mergers of smaller halos gradually lead to the structures observed today
- The halo mass function depends somewhat on the cosmological parameters, but otherwise can be reliably calculated



Reed et al., MNRAS, astro-ph/0607150

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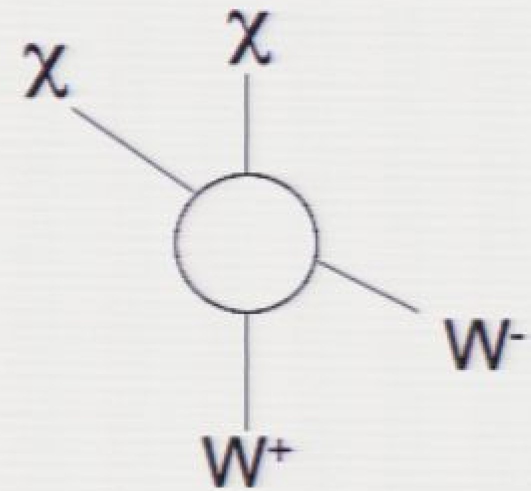
Ionizing Radiation From WIMP Annihilations

1. **WIMP Annihilation**
   Typical final states include heavy fermions, gauge or Higgs bosons



Ionizing Radiation From WIMP Annihilations

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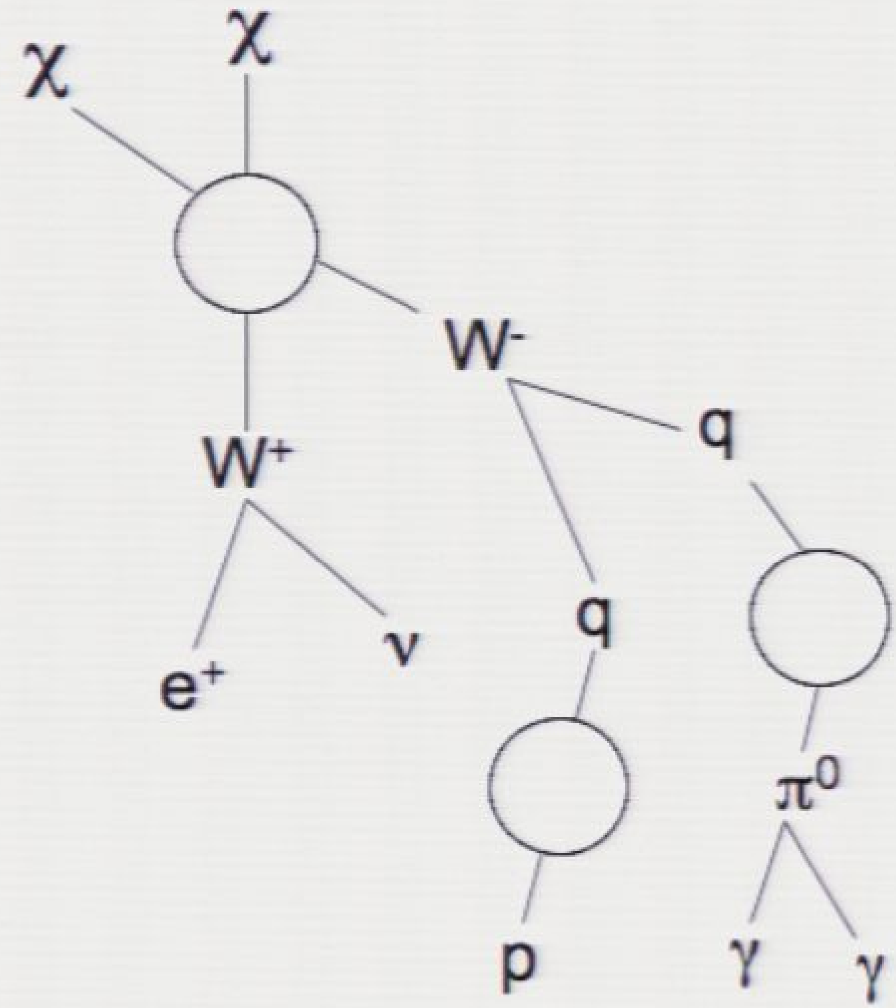

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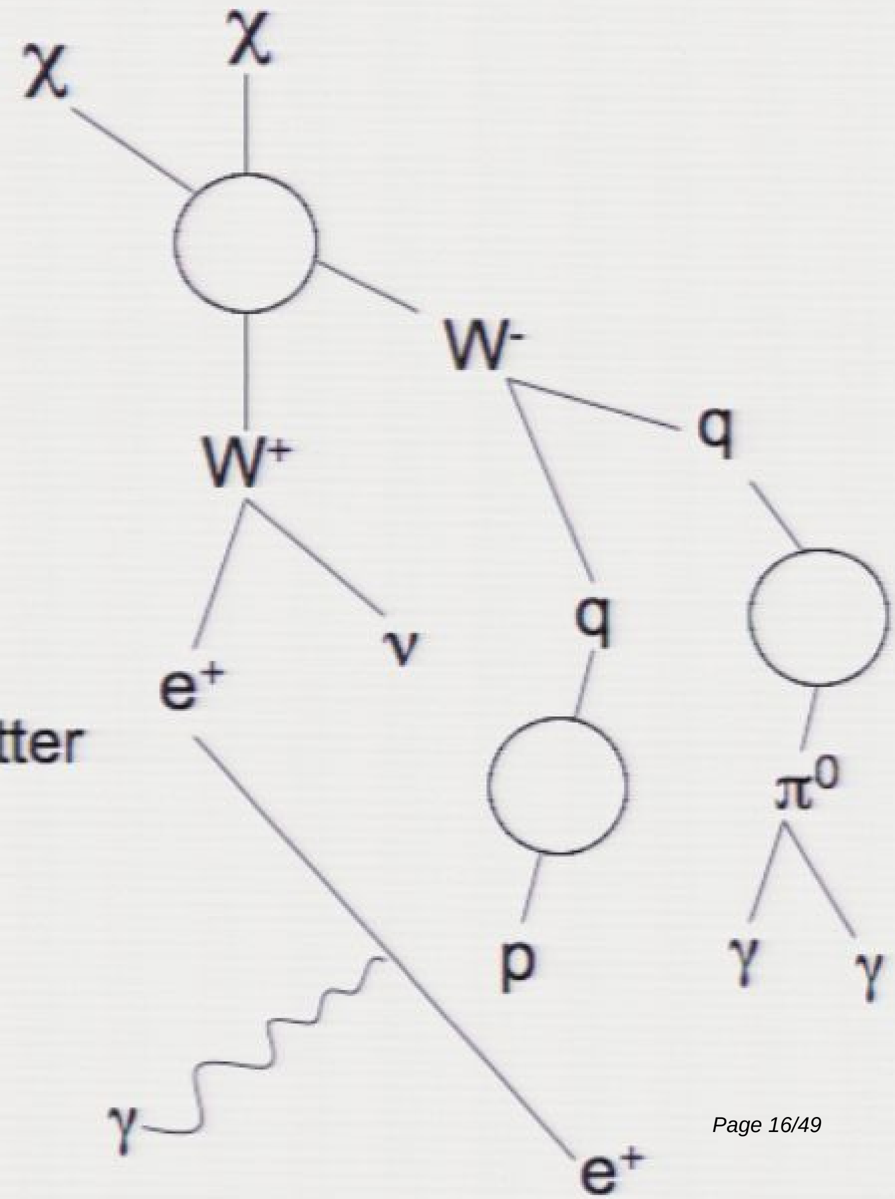
3. **Inverse Compton Scattering**
   Relativistic (~GeV) electrons up-scatter CMB photons to ~MeV energies



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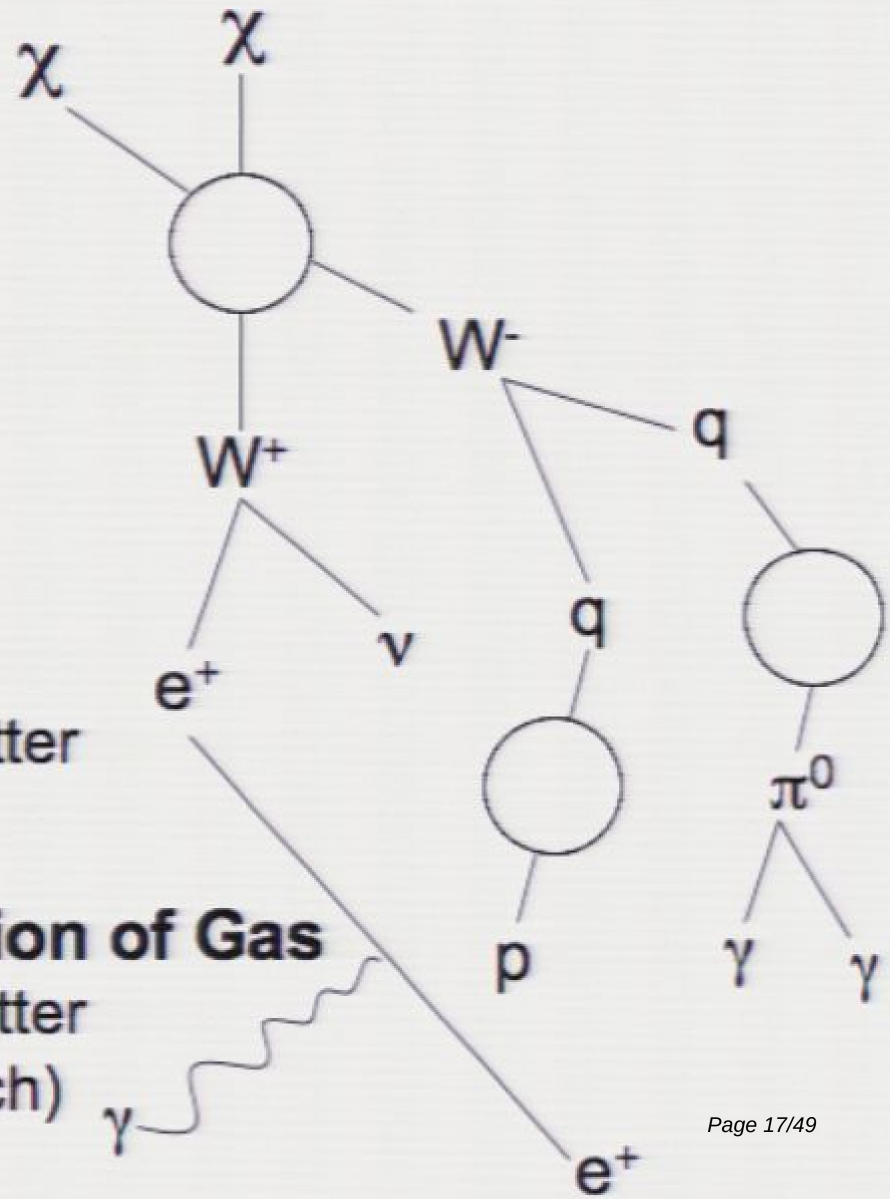
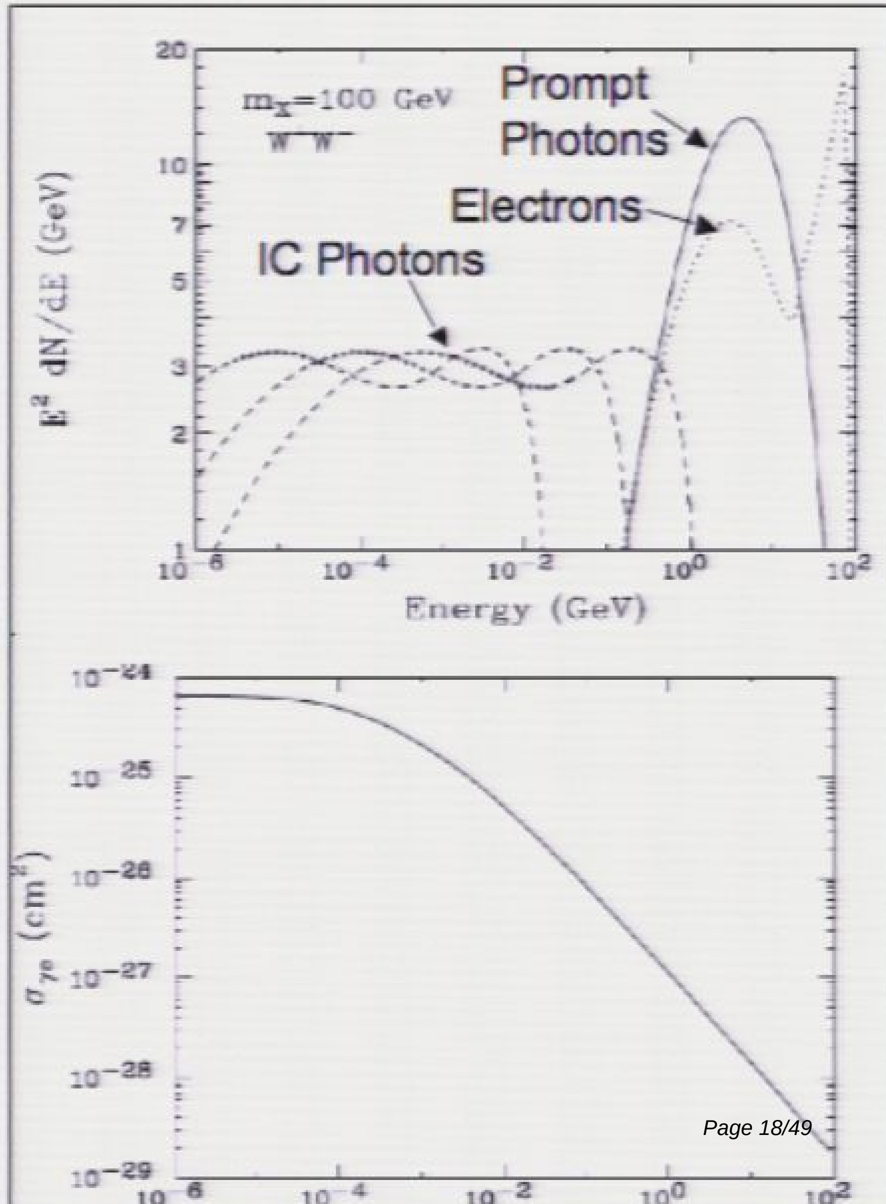
4. **Ionization, Heating and Excitation of Gas**
   Some of these photons go on to scatter with electrons (~1/3 of energy to each)



The Relative Importance of Inverse Compton Photons

- Most dark matter annihilation channels lead to a similar quantity of energy being deposited in photons and electrons
- The electrons eventually transfer their energy into a large number of lower energy photons via inverse Compton scattering with the CMB
- As the photon-electron cross section is much larger at lower energies, a much larger fraction of the IC photons' energy goes into ionizing atoms



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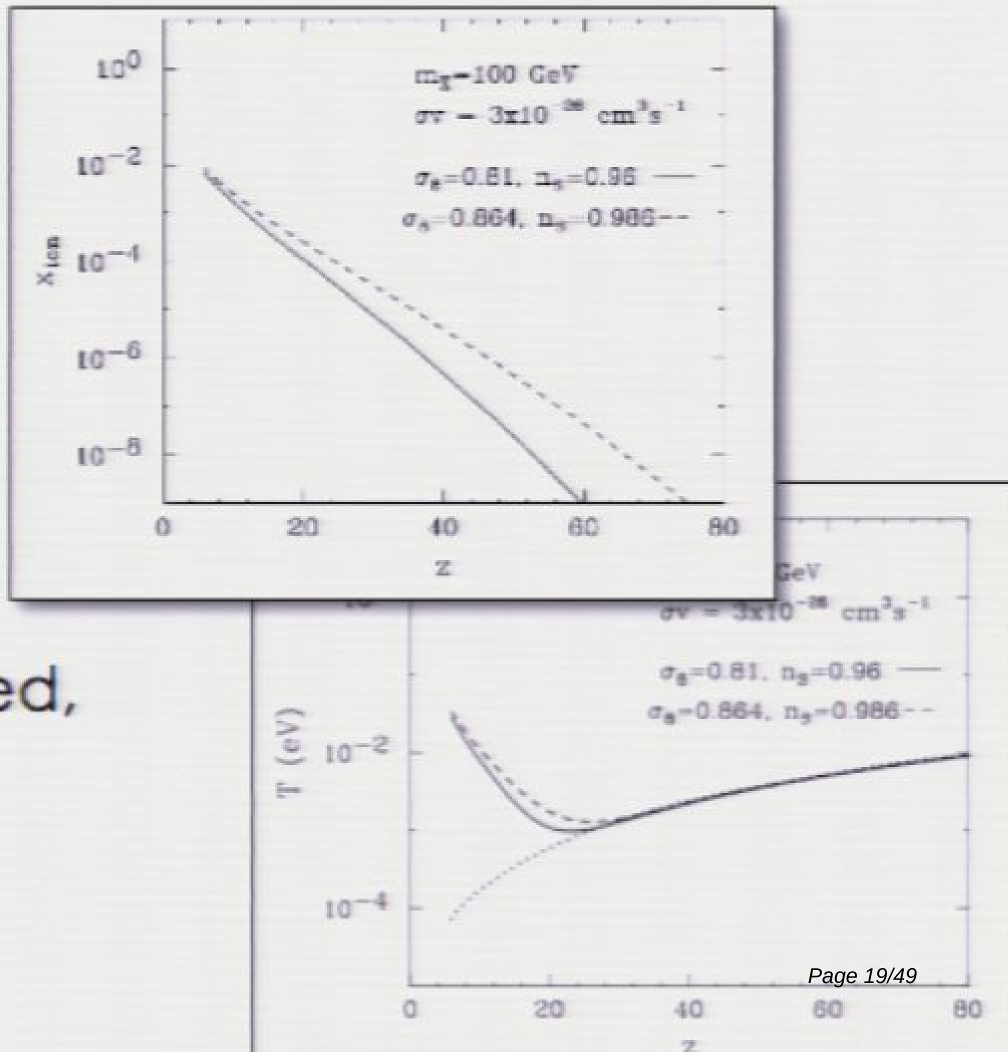
Case Example: A Typical SUSY Neutralino

- Consider a typical ~100 GeV neutralino which annihilates to W^+W^- with a cross section of $\sigma v \sim 3 \times 10^{-26}$ cm^3/s

- For such a WIMP, annihilations in the first billion years of our universe's history lead to only ~1% of the atoms being reionized, and only mild heating



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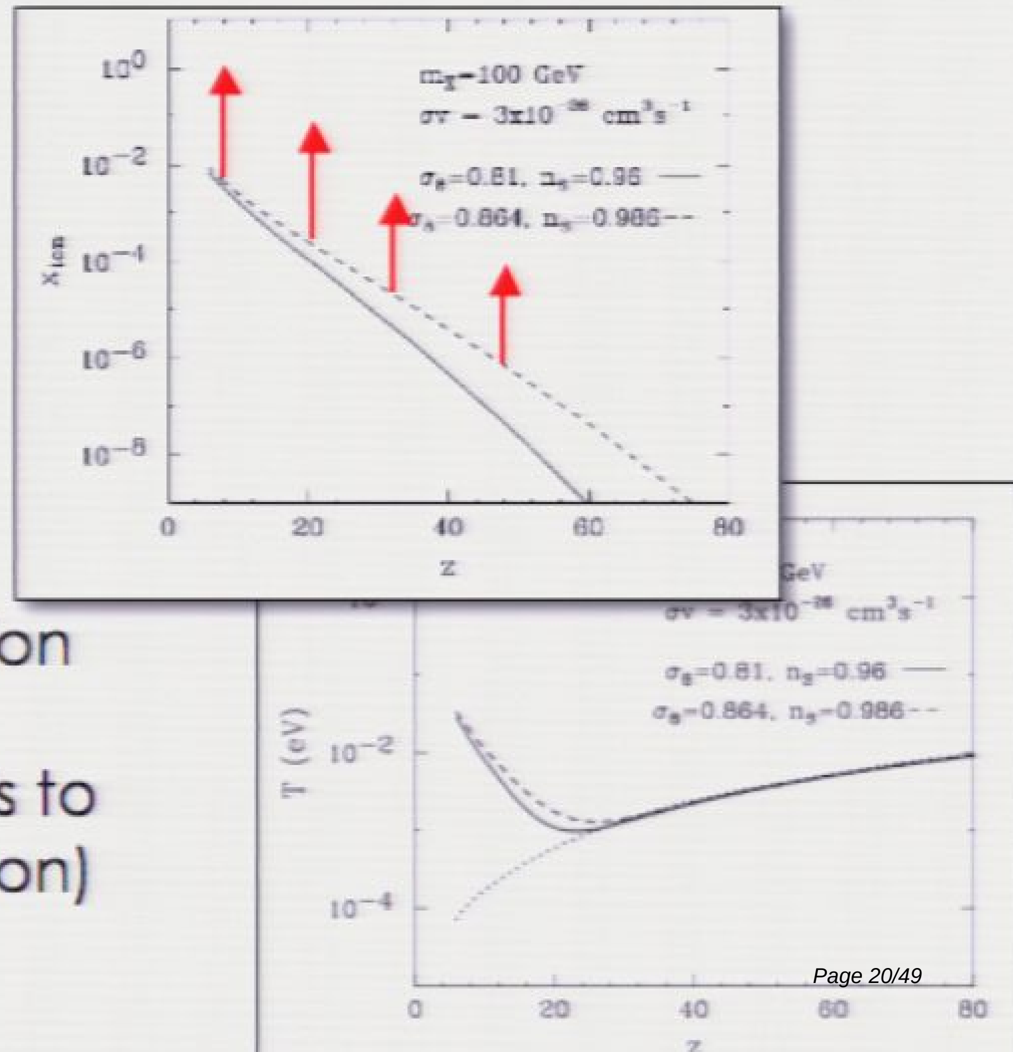
Efficiently Ionizing Dark Matter Candidates

To provide the majority of the radiation that reionized the universe, we need another kind of WIMP



For example, we could consider WIMPs with:

- A considerably larger annihilation cross section
- Dominant annihilation channels to electrons (more inverse Compton)

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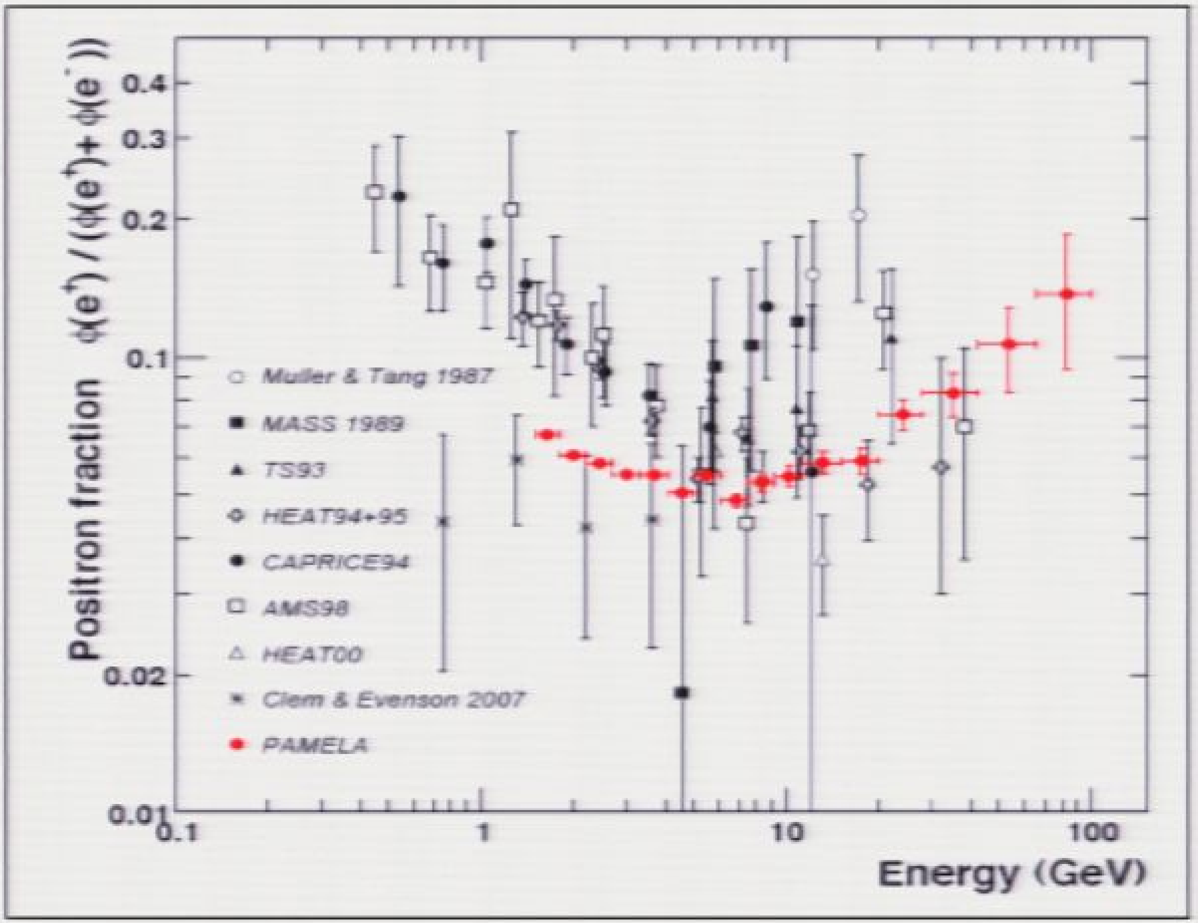
But what possible motivation could we have for such a dark matter candidate?

Pamela's Cosmic Ray Positron Measurement



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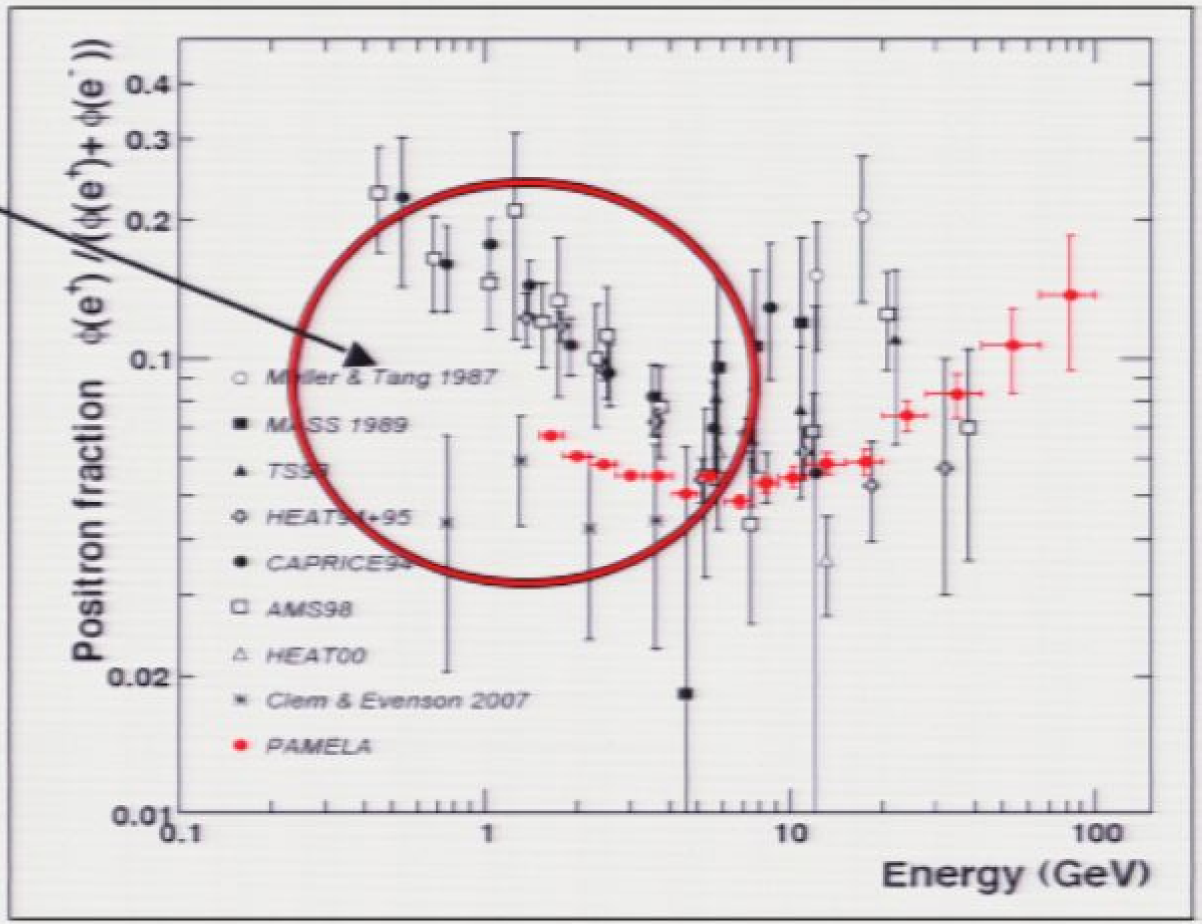
Pamela Collaboration, arXiv:0810.4995

Pamela's Cosmic Ray Positron Measurement

- First glance: Is this all screwed up?
- Charge-dependent solar modulation important below 5-10 GeV!

(Pamela's sub-10 GeV positrons appear as they should!)



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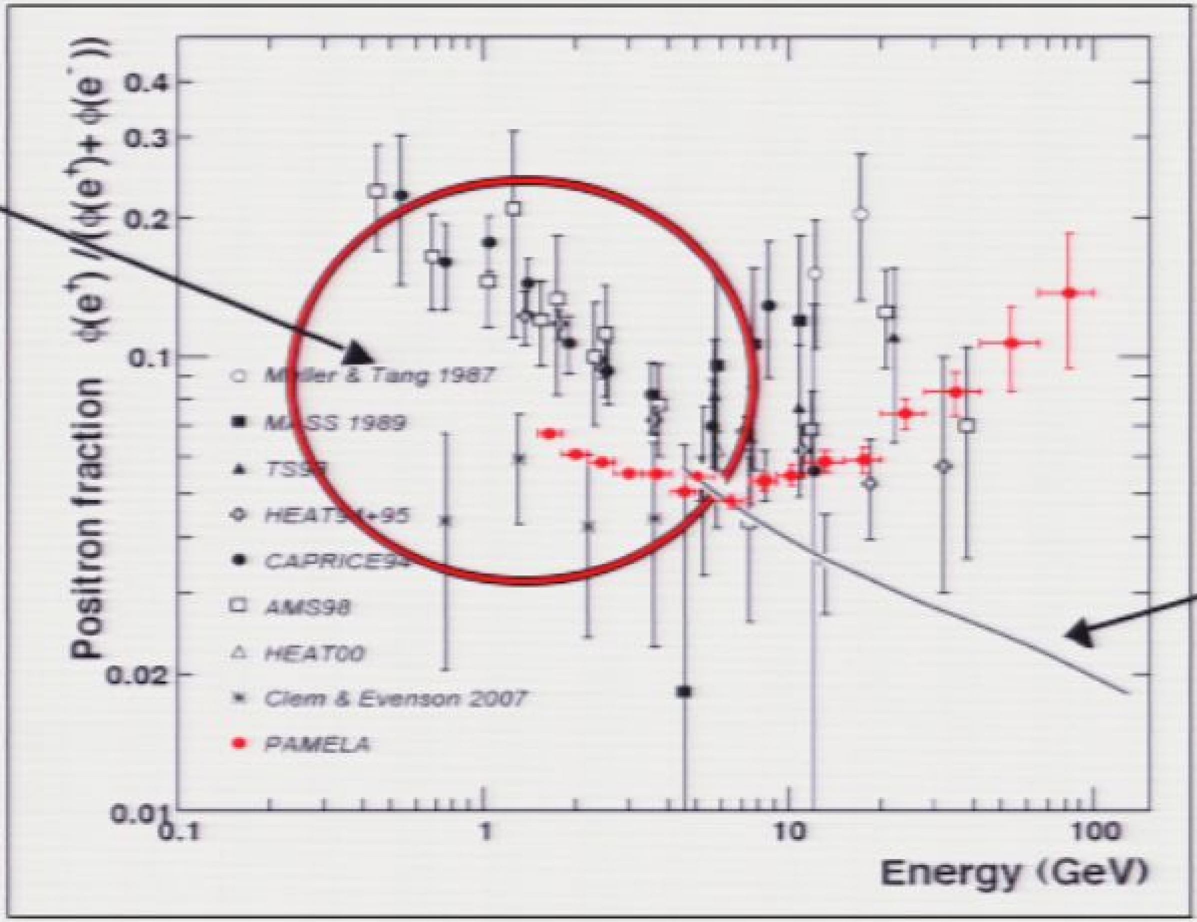

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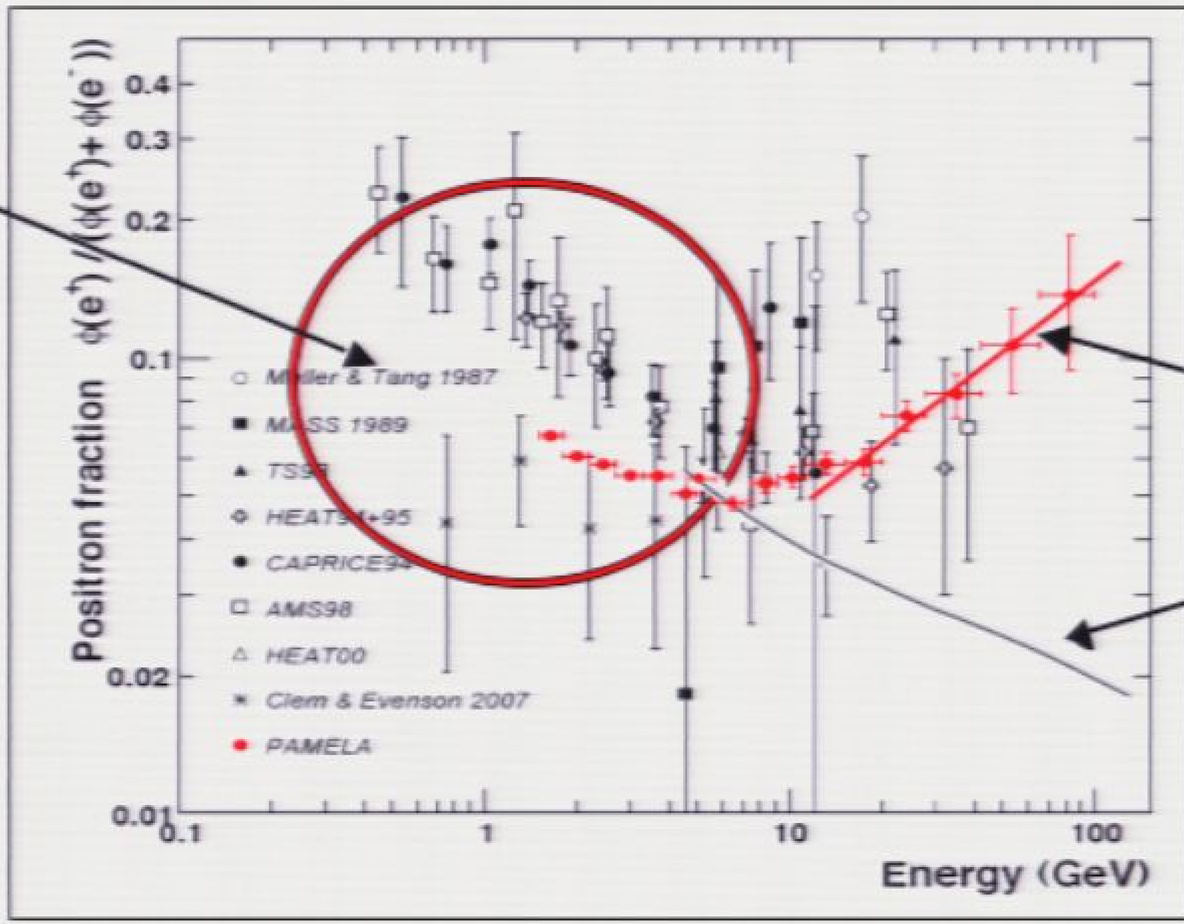

Rapid climb above 10 GeV indicates the presence of a <u>primary source of cosmic ray positrons!</u>

Astrophysical expectation (secondary production)

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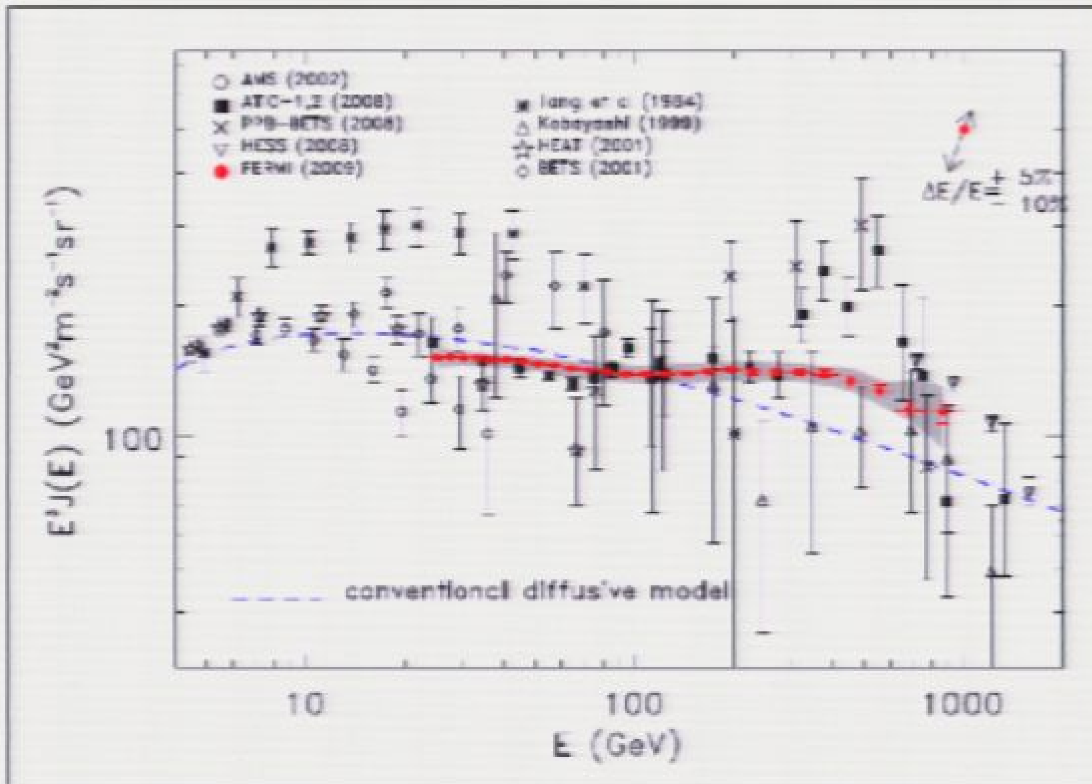
Pamela Collaboration, arXiv:0810.4995

The Cosmic Ray Electron Spectrum

- In a series of balloon flights, ATIC measured an excess of cosmic ray electrons between 300 and 800 GeV (Nature, Nov. 21, 2008)

- New results from the Fermi Gamma Ray Space Telescope (and HESS) measure a less pronounced feature, but still an excess



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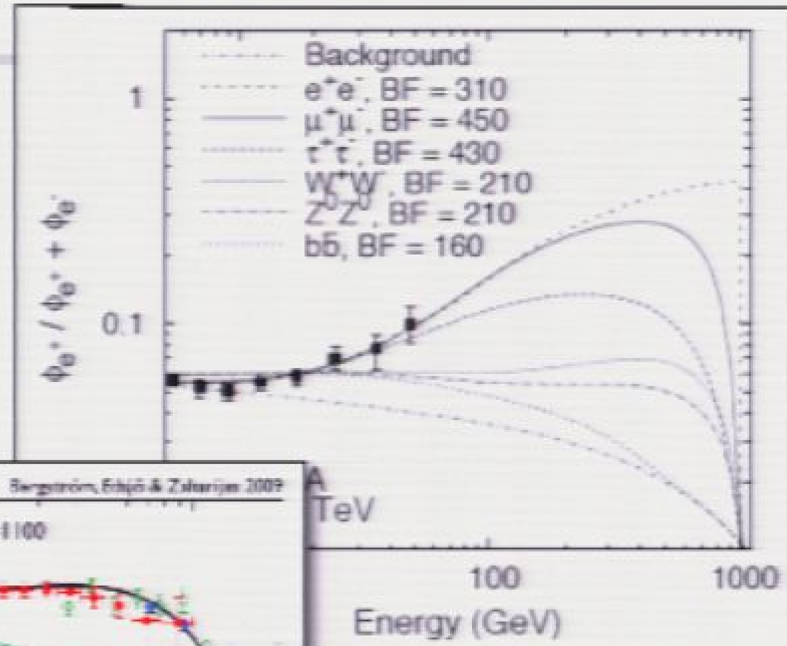
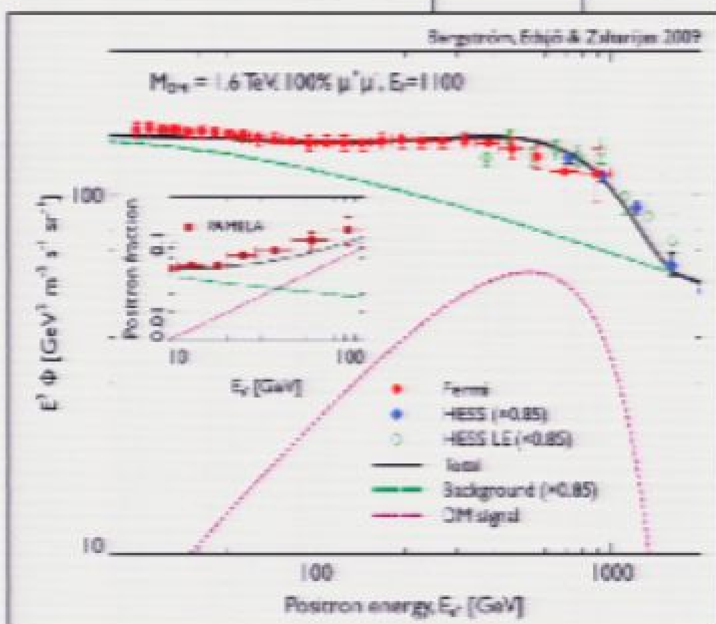
Dark Matter as the Source of the Pamela and/or Fermi Signals

- The positrons/electrons observed by Pamela and Fermi could be generated by dark matter annihilations,…

but to do so would require the dark matter to have some rather special properties



Cholis, Goodenough, Hooper, Simet, Weiner arXiv:0809.1683



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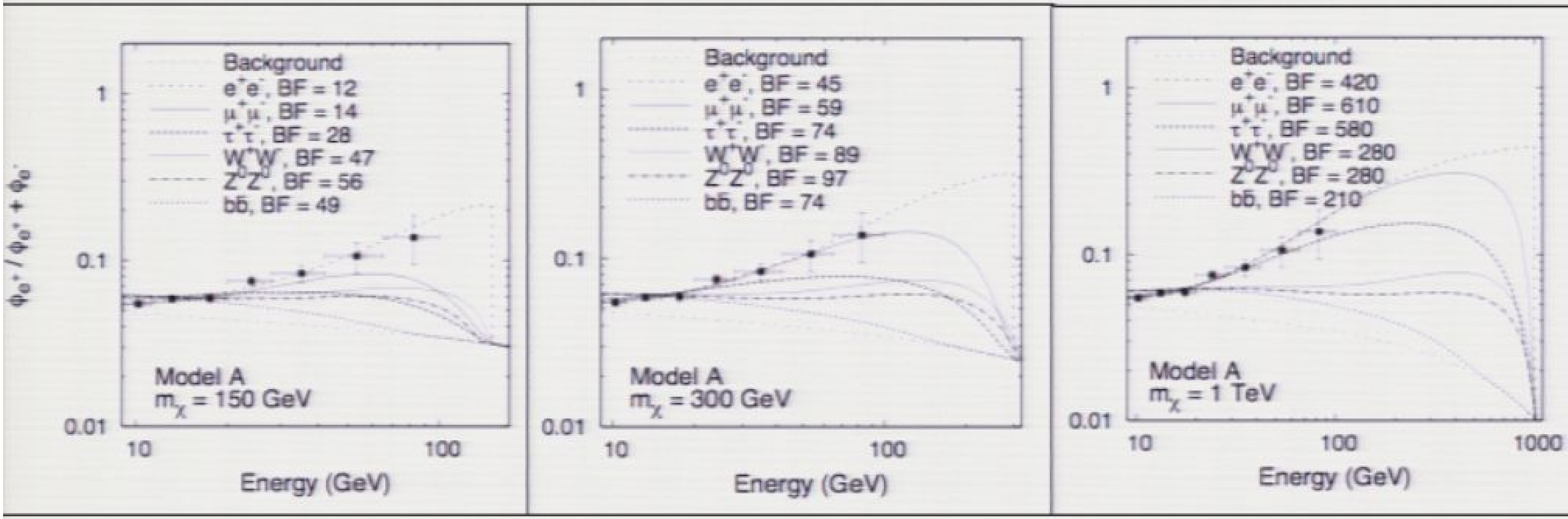
Bergstrom, Edsjo, Zaharijas, arXiv:0905.0025

Dark Matter as the Source of the Pamela and Fermi Signals

- To produce the observed positron excess, dark Matter annihilations must proceed mostly to charged leptons



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Cholis, Goodenough, Hooper, Simet and Weiner,

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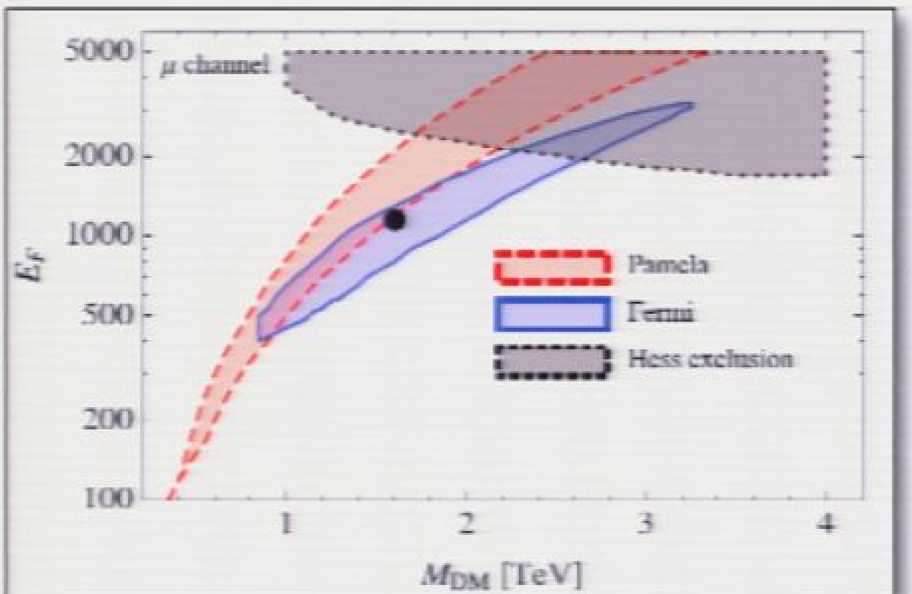

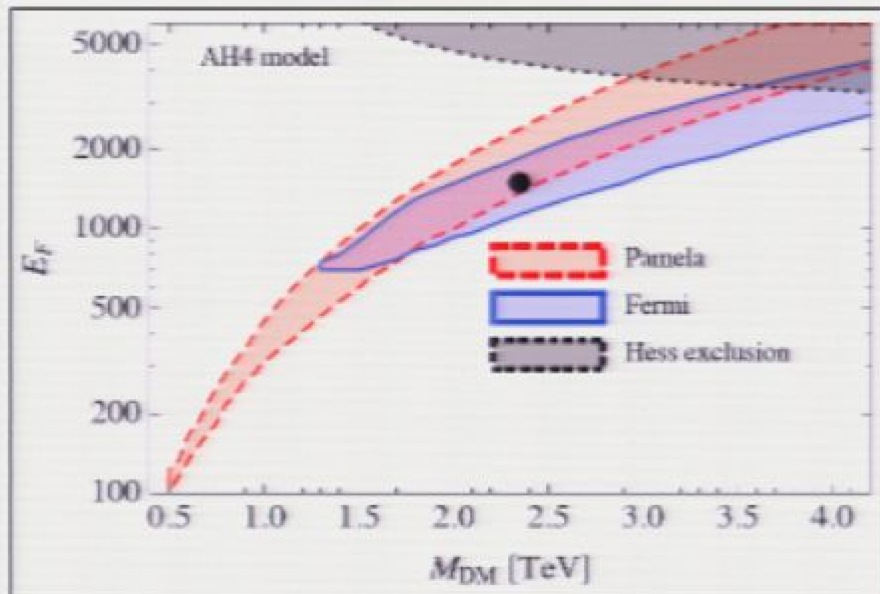

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Bergstrom, Edsjo, Zaharijas, 2009

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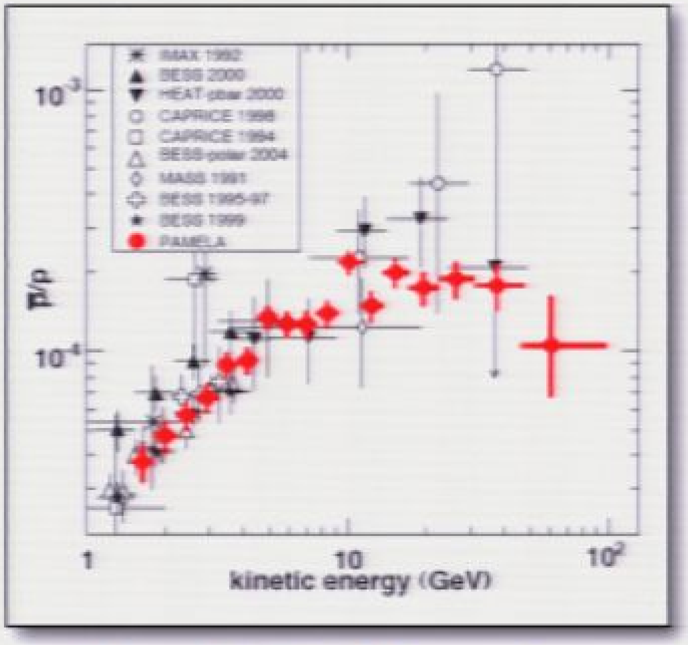
- The Fermi spectrum (if explained by dark matter), requires TeV-scale WIMPs that annihilate to $\mu^+\mu^-$
- Annihilations to leptons also enable the stringent constraints from antiproton, gamma ray and synchrotron measurements to be evaded



Pamela Collaboration, arXiv:0810.4994

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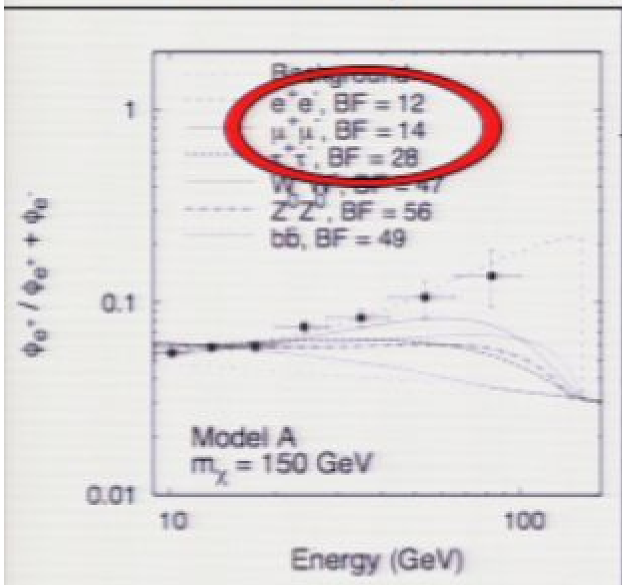
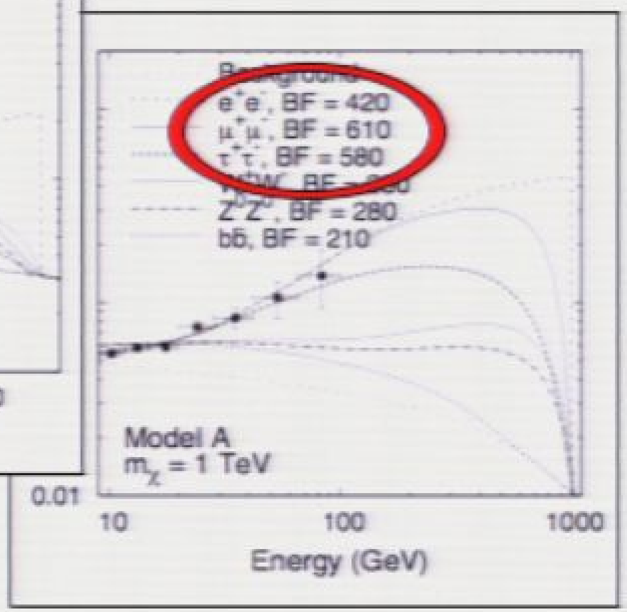
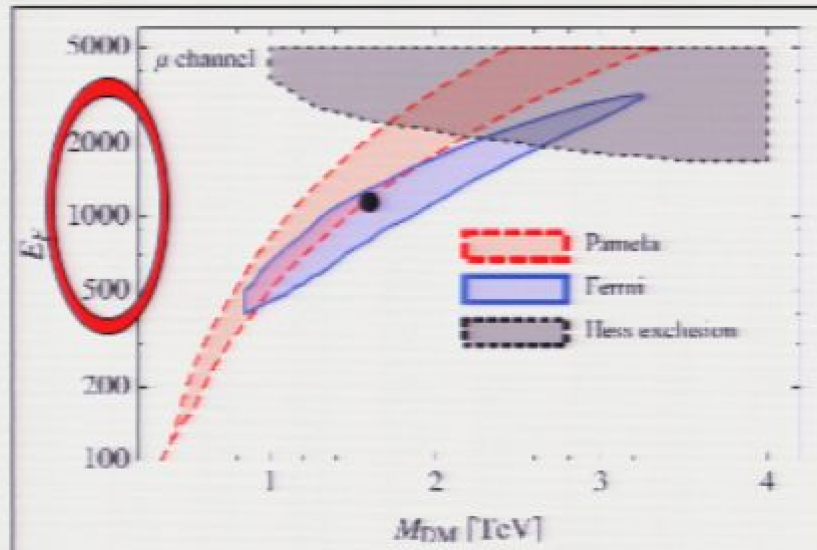
Dark Matter as the Source of the Pamela and/or Fermi Signals

- The PAMELA/Fermi signals also require very large annihilations rates compared to that expected from a typical thermal relic







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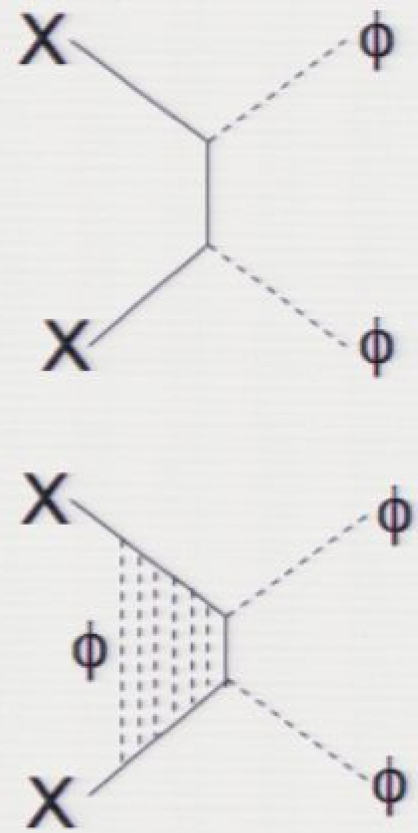
Cholis, Goodenough, Hooper, Simet and Weiner, 2008; Bergstrom, Edsjo, Zaharijas, 2009

Dark Matter as the Source of the Pamela and Fermi Signals

One possible solution:

- Annihilation rate dramatically increased by non-perturbative effects known as the "Sommerfeld Enhancement"
  - Very important for $m_\phi << m_X$ and $v_X << c$ (such as in the halo, where $v_X/c \sim 10^{-3}$)



Arkani-Hamed, Finkbeiner, Slatyer, Weiner, arXiv:0810.0713;
Cirelli and Strumia, arXiv:0808.3867

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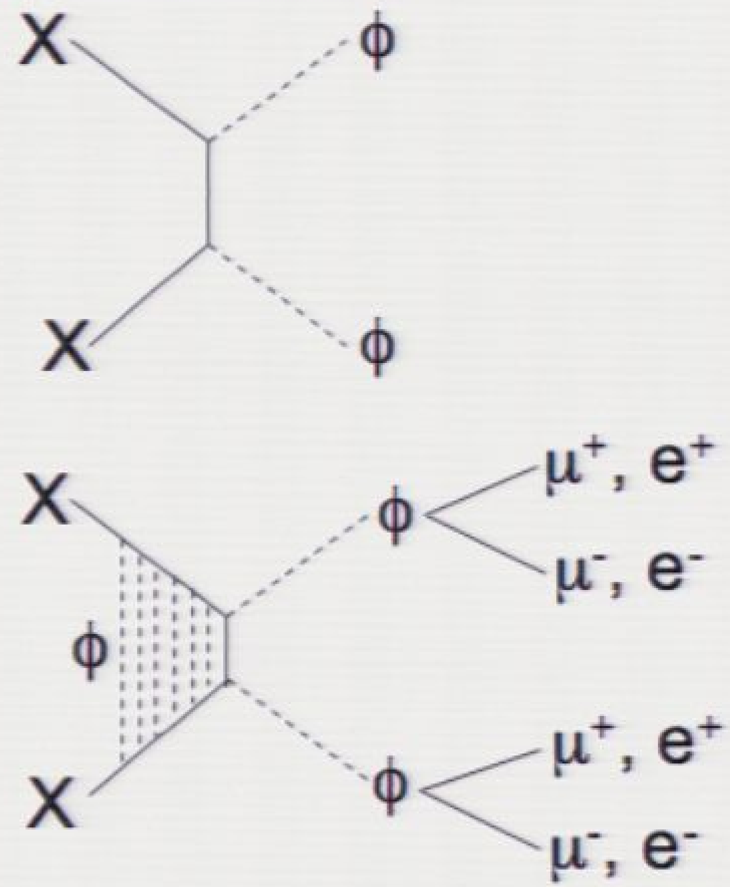

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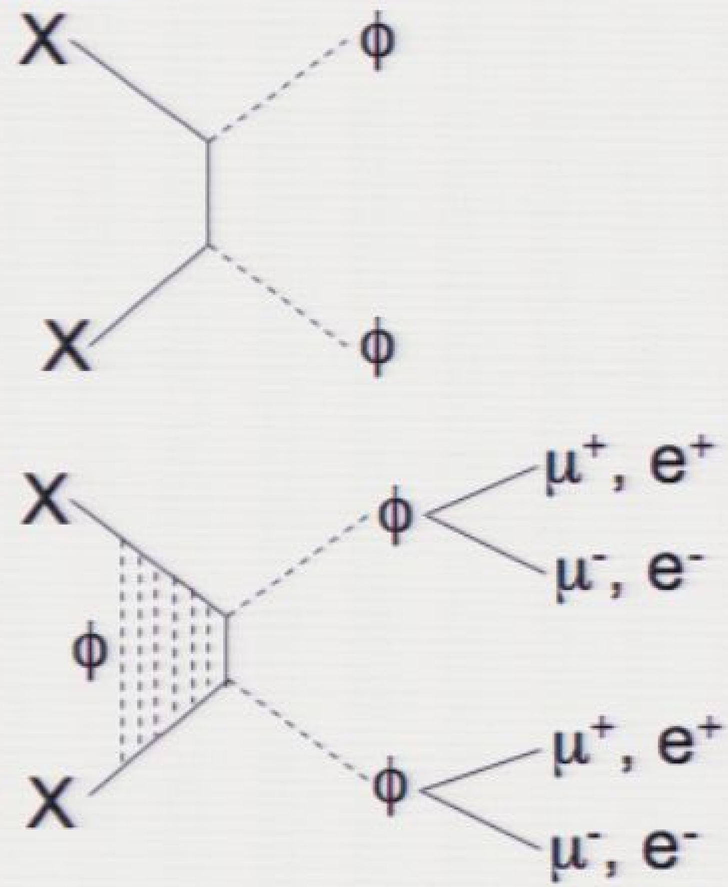

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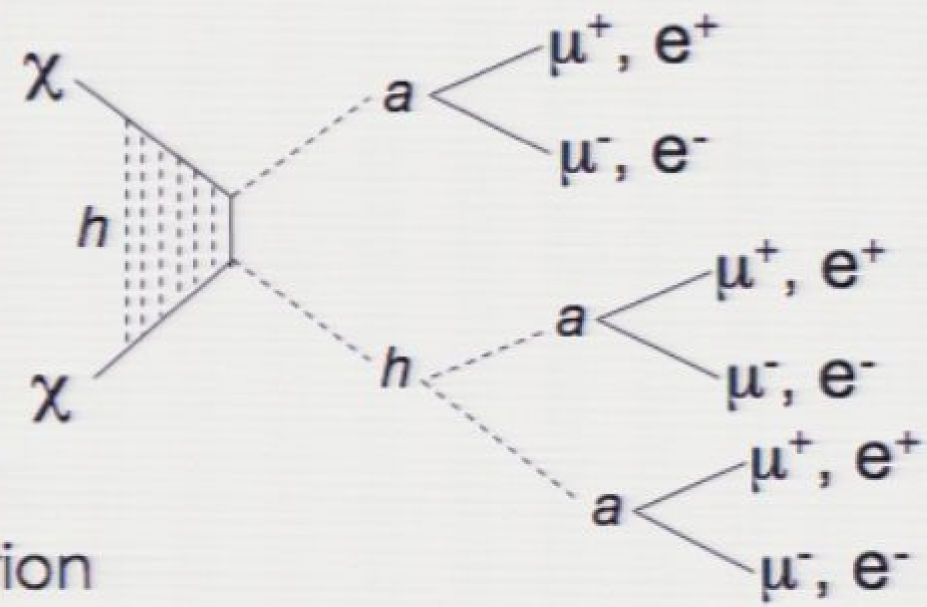
Dark Matter as the Source of the Pamela and Fermi Signals

A Supersymmetric Realization:

- In the MSSM extended by a higgs singlet, the LSP can be a singlino, coupled to light singlet-like scalar (h) and psedoscalar (a) higgs bosons
- Can provide the PAMELA/FGST signals, including large annihilation rate via a higgs induced Sommerfeld effect



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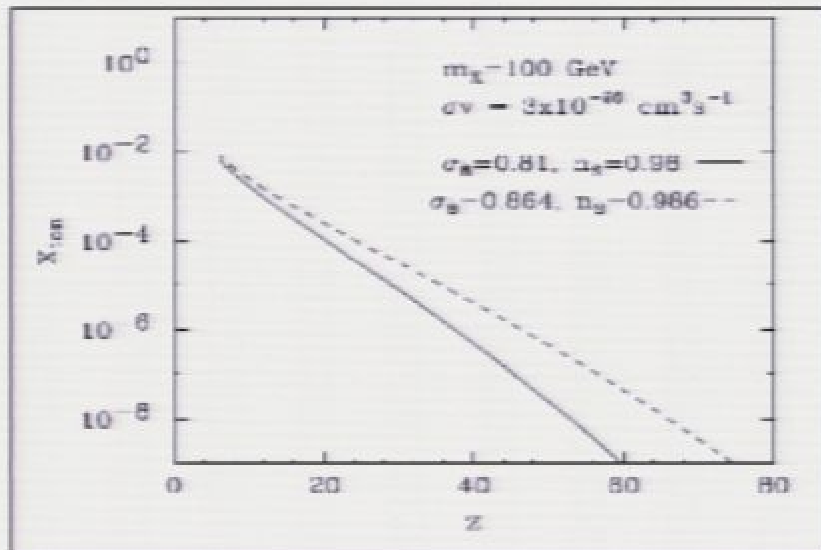
Hooper and T. Tait, arXiv:0906.0362

What Effect Would Such A WIMP Have On Reionization?

- Recall that a typical ~100 GeV WIMP which annihilates to W^+W^- with a cross section of $\sigma v \sim 3 \times 10^{-26}$ cm^3/s only reionizes ~1% of atoms by z=6



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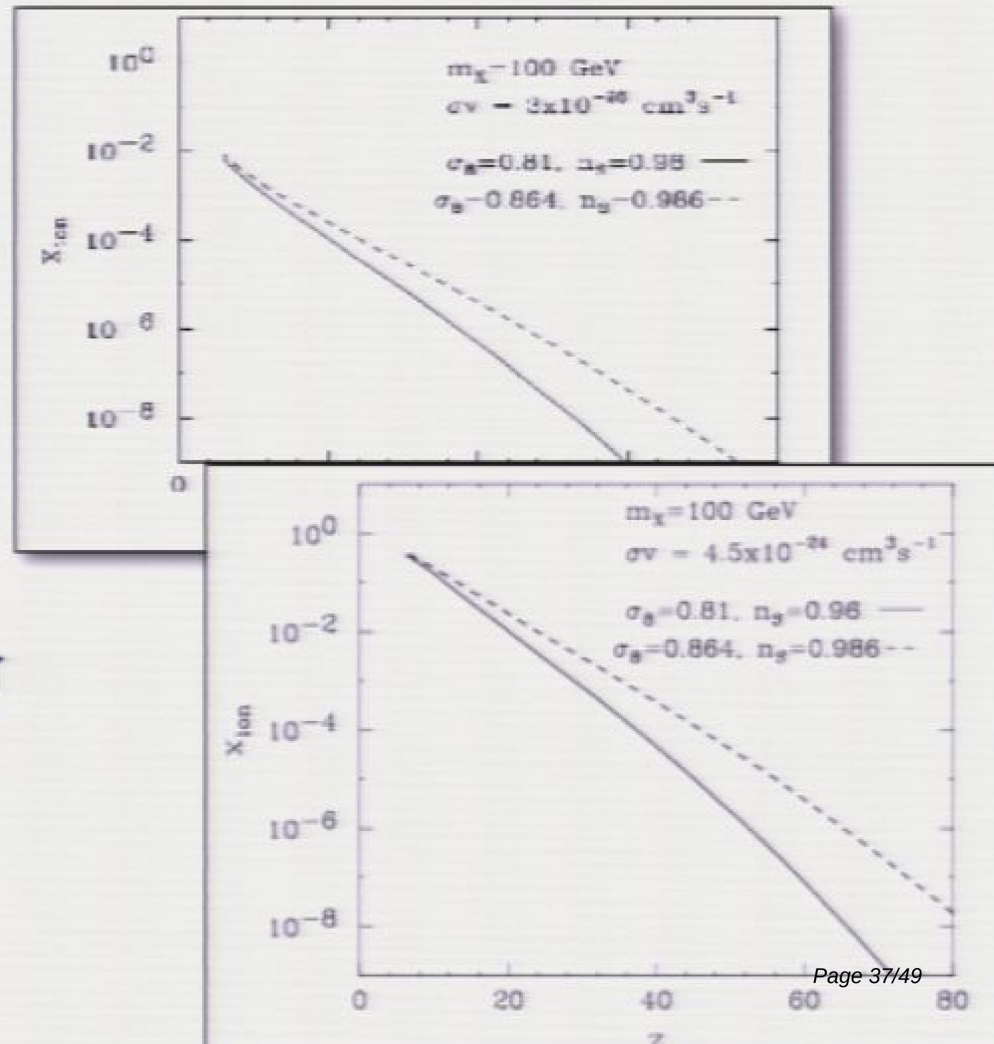
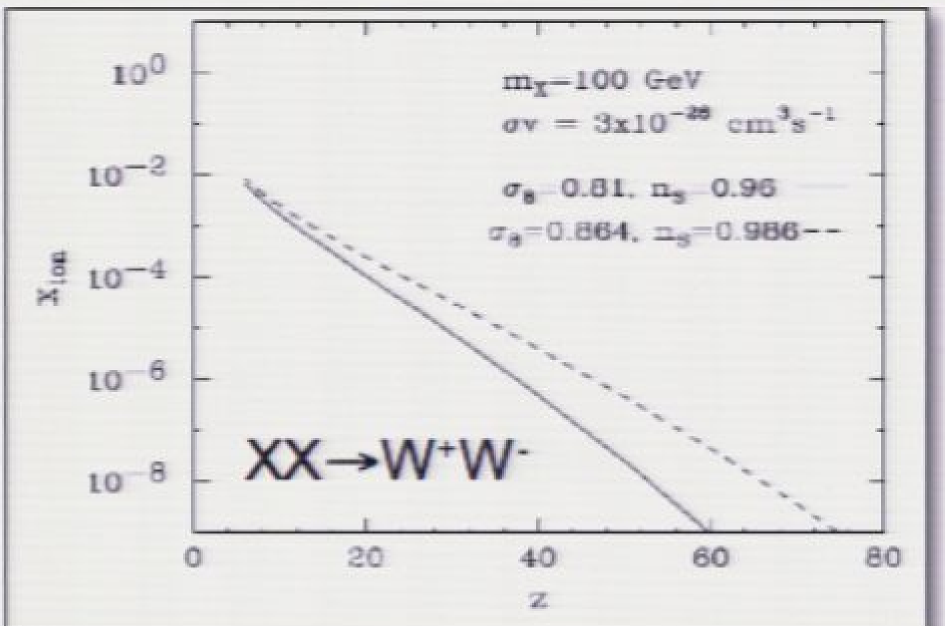
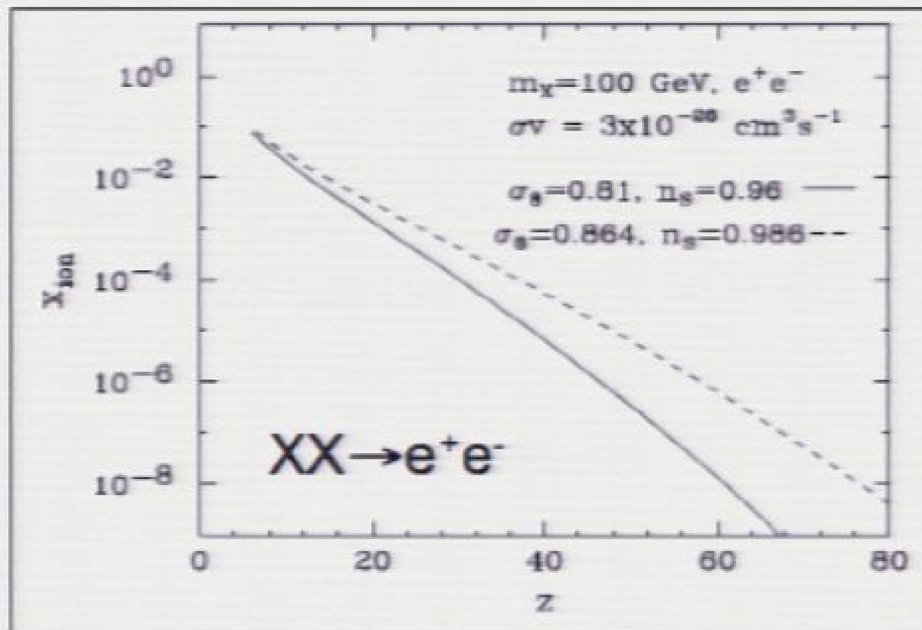
- If we boost the cross section by a factor of $\sim 10^2$ (a non-thermal wino-like neutralino, for example), we find that dark matter can be the dominant source of reionization



What Effect Would Such A WIMP Have On Reionization?

- WIMPs annihilating directly to electrons are far more efficient in reionizing gas (by a factor of ~10)





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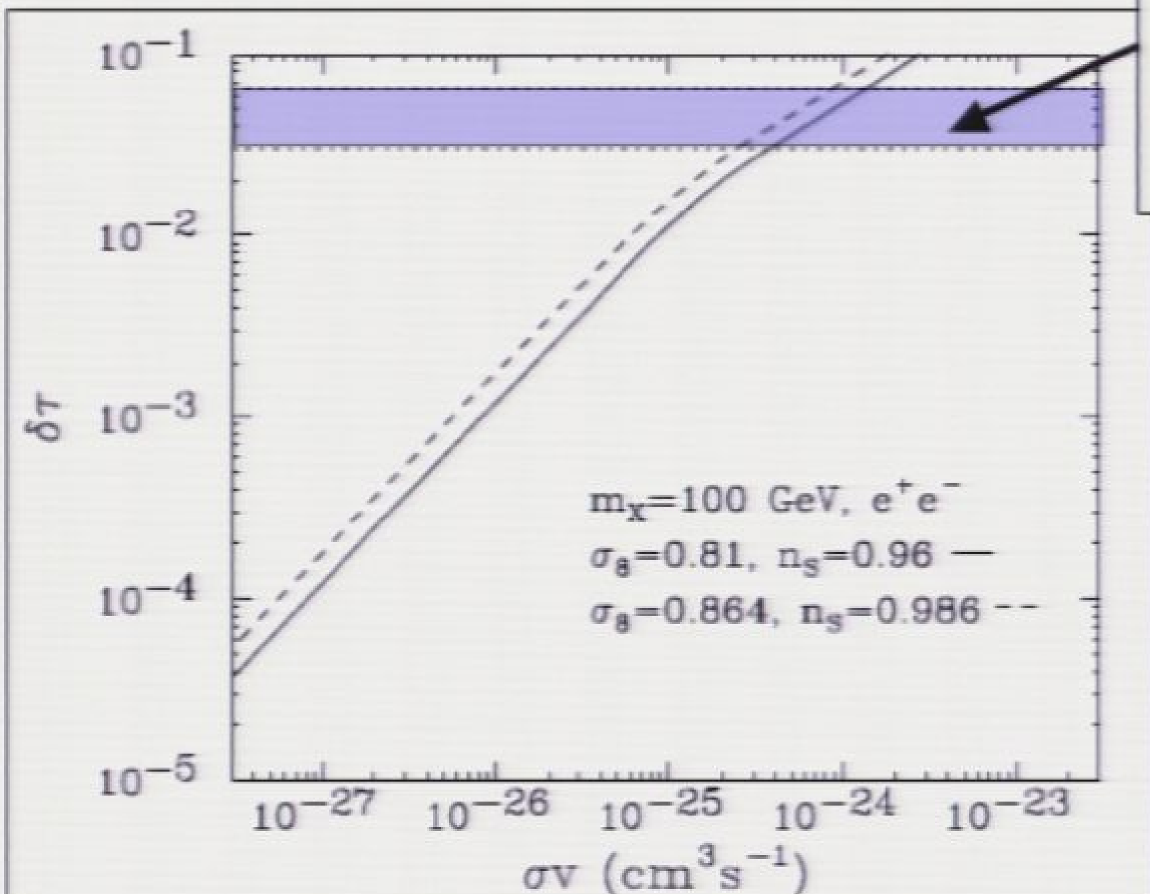

Observed degree of reionization (z>6)
(WMAP optical depth)

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Belikov and Hooper, arXiv:0904.1210

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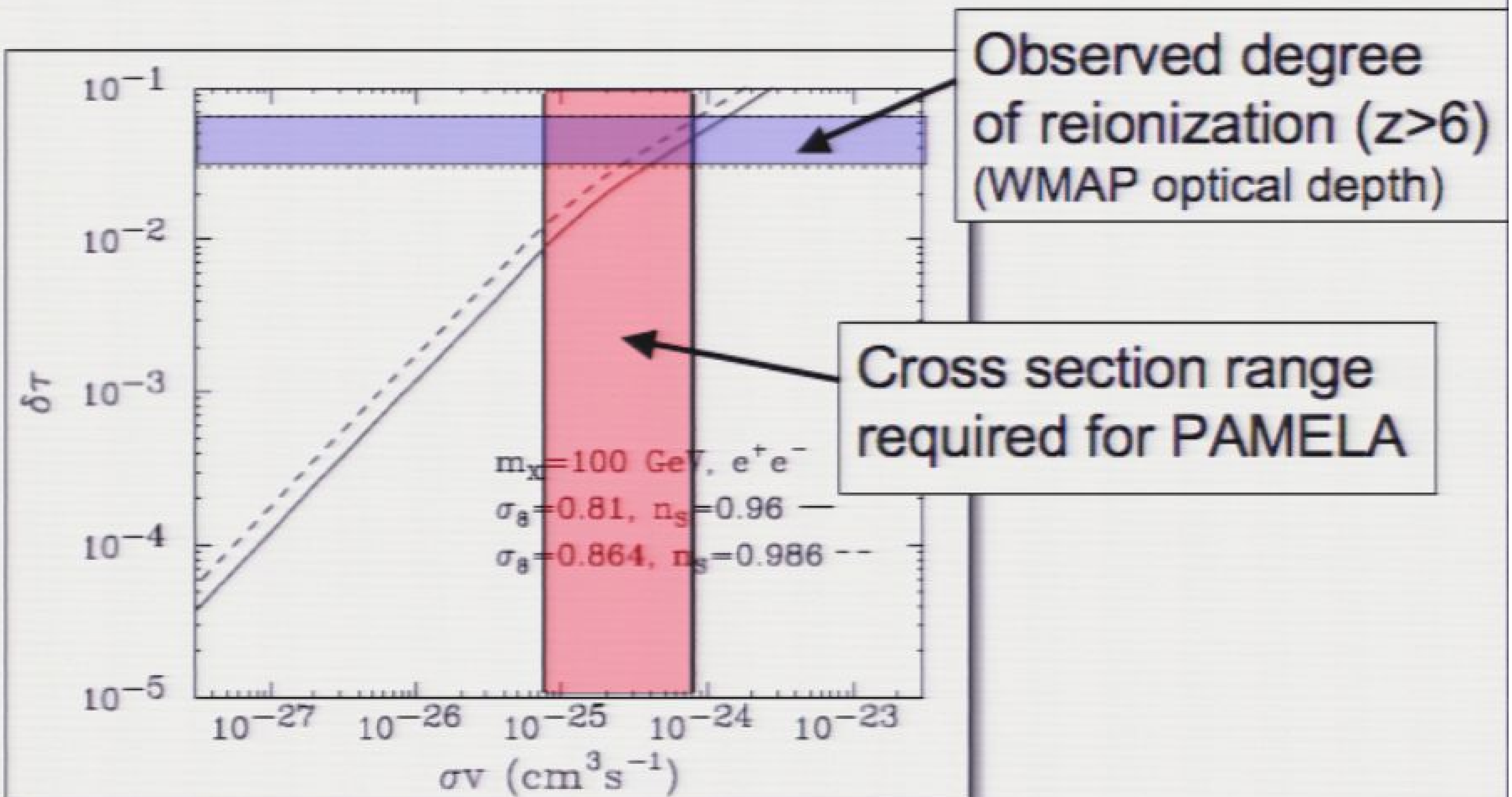

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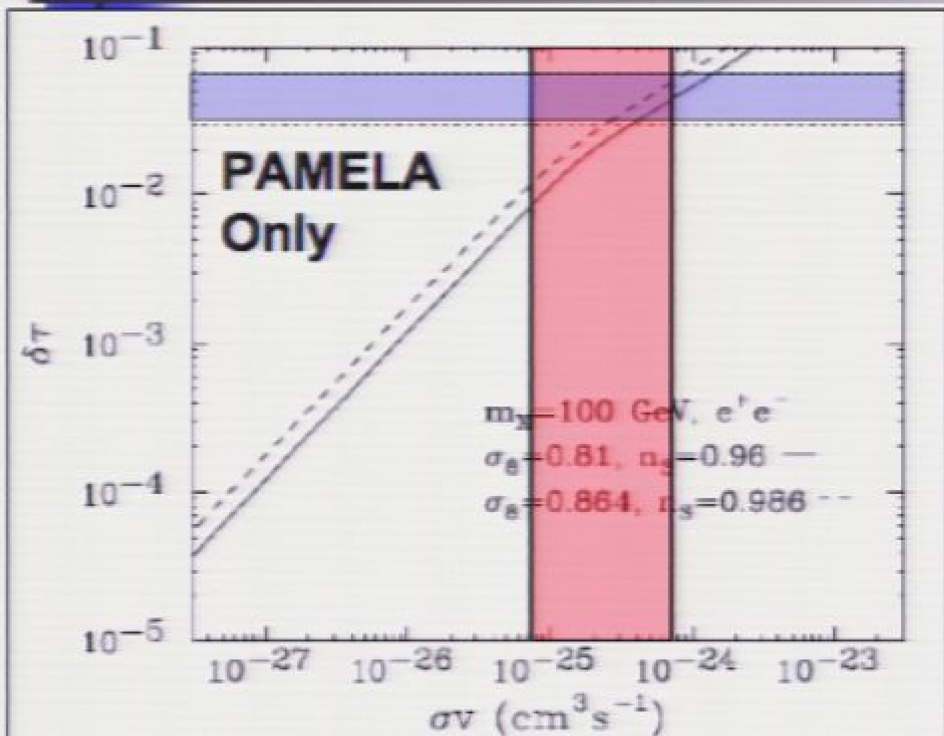
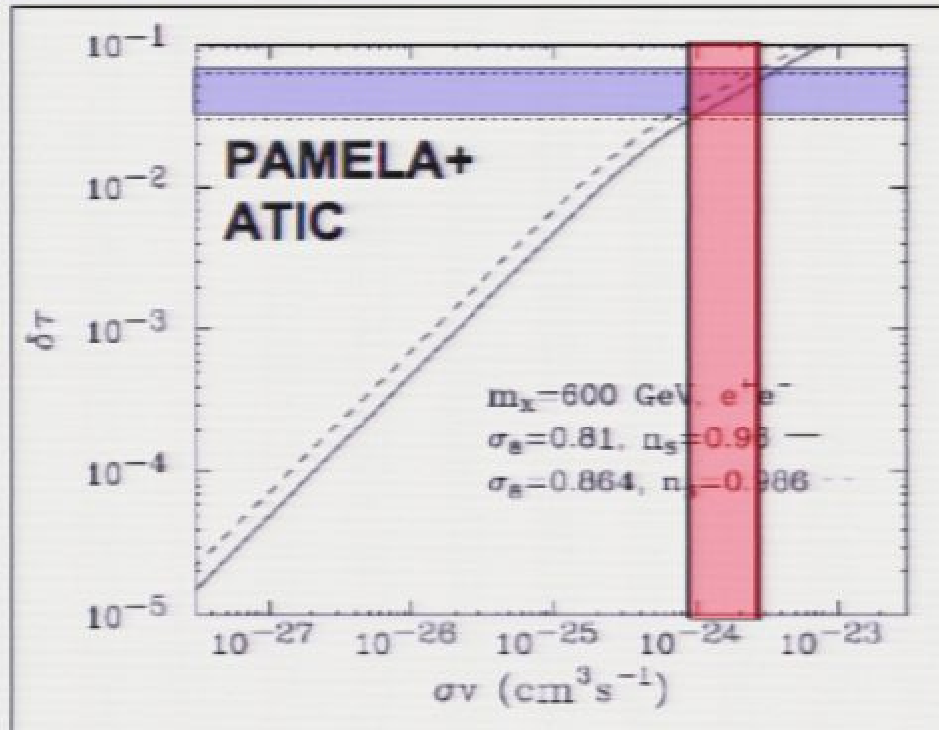
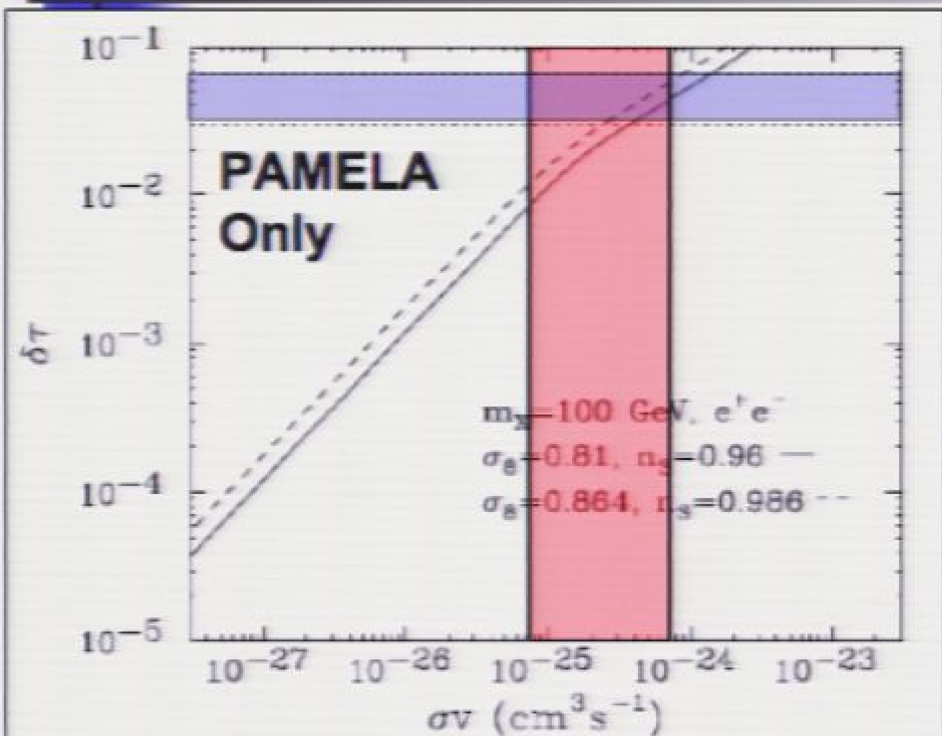


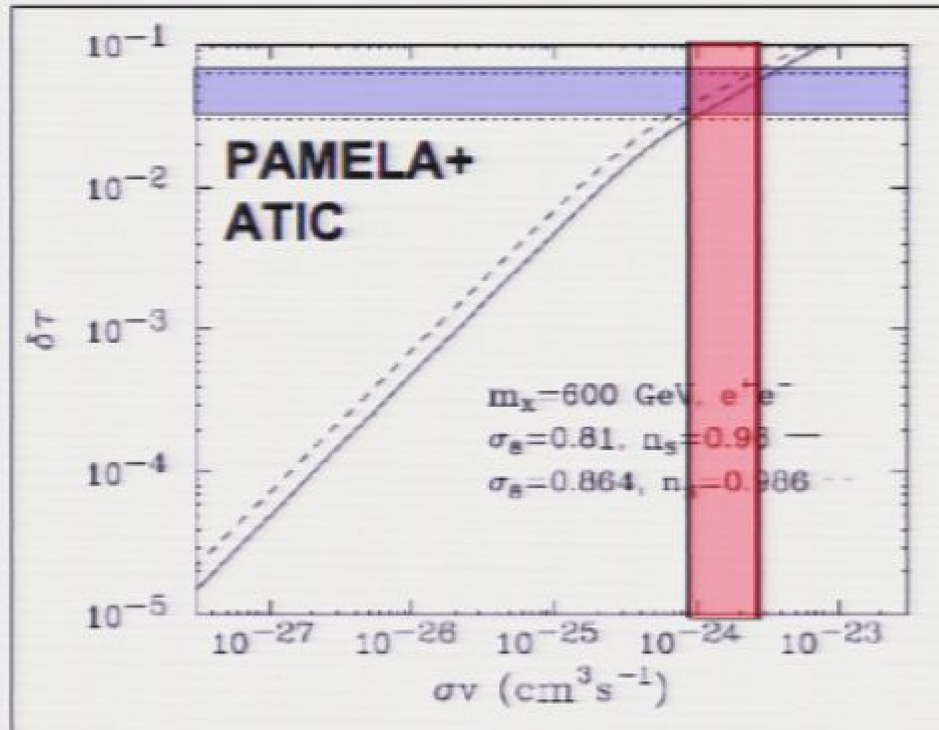


Dan Hooper - *Did Dark Matter*

Belikov and Hooper, arXiv:0904.1210

Did Dark Matter Reionize Our Universe?





If annihilating dark matter is responsible for the PAMELA (or ATIC) signals, then dark matter is also predicted to have played a dominant role in reionizing the universe!

Dan Hooper - *Did Dark Matter*

Belikov and Hooper, arXiv:0904.1210

(Modest) Uncertainties

- Cosmological parameters (σ_8, η_s) impacting the halo mass function
- Clumping of gas (impact on recombination rate)
- Halo profile/concentration

Open Questions/Areas For Future Inquiry

- How does the fraction of doubly ionized helium evolve with redshift?

- A closer look at gas heating - both modeling and constraints

- From the WMAP optical depth measurement, what constraints can be placed on the dark matter annihilation cross section/channels?

Future Experiments!

·Planck will considerably refine the optical depth measurements, perhaps even providing information in redshift bins

·The Fermi Gamma Ray Space Telescope will study the extragalactic diffuse gamma ray background - If dark matter reionized the universe, it will also have generated a very bright background

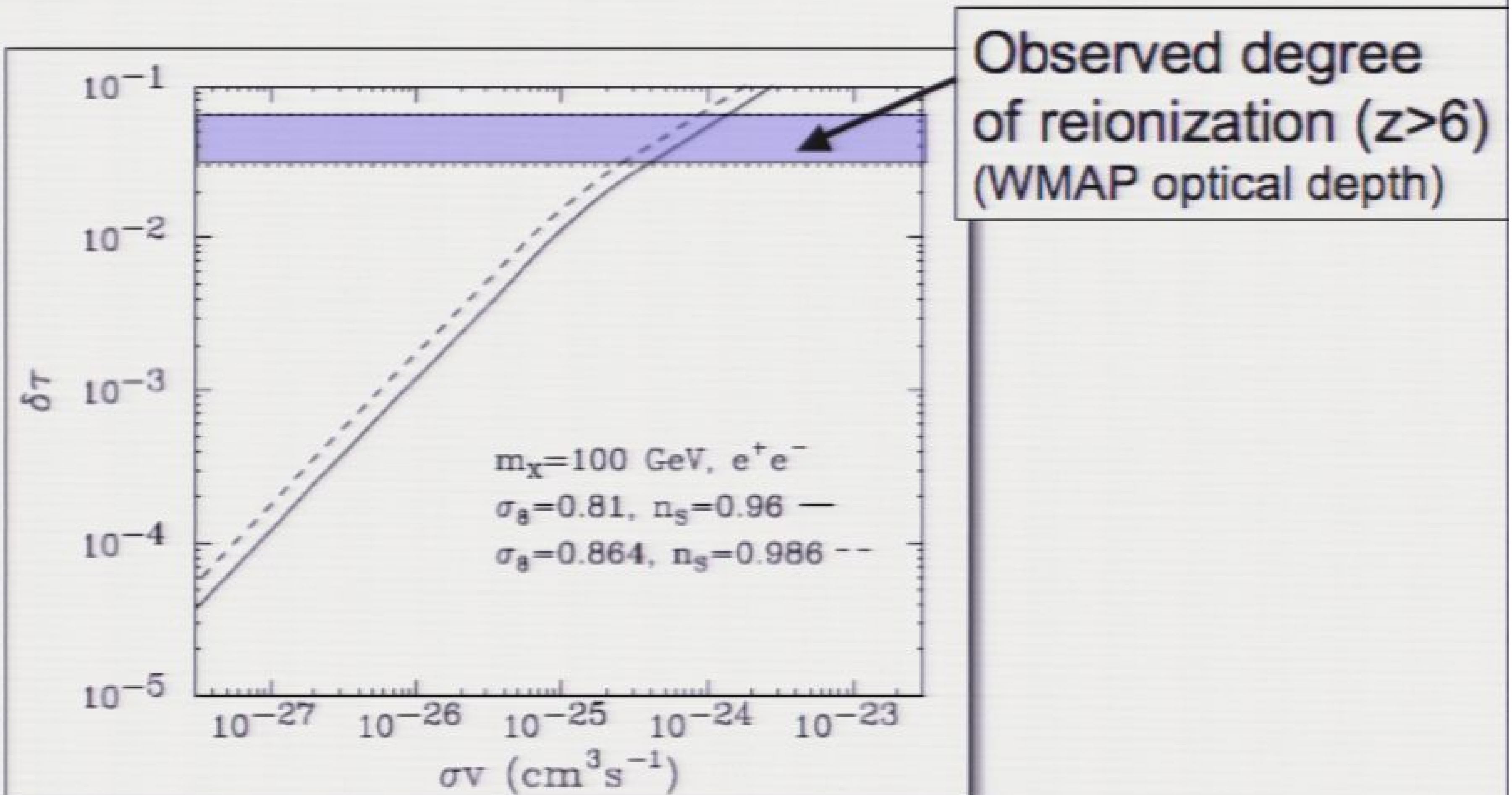
·21 cm emission from neutral gas falls in the radio range (1.4 GHz)/(1+z) - Very large radio observatories may be able to map out the history of reionization

Dan Hooper - *Did Dark Matter Annihilations Reionize The Universe?*

Summary

- Between ~200 million and ~1 billion years after the big bang, the baryonic gas in our universe was almost entirely reionized - the source(s) of the responsible radiation may include quasars, early stars, and/or dark matter annihilations
- Dark matter annihilations in typical thermal WIMP scenarios lead to only ~1% of the gas becoming ionized
- WIMPs which annihilate primarily to leptons are ~10 times more efficient at ionizing gas (importance of inverse Compton scattering!)
- If dark matter is responsible for the PAMELA positron excess, then it is also expected to have played a major role in the reionization of our universe

Did Dark Matter Reionize Our Universe?



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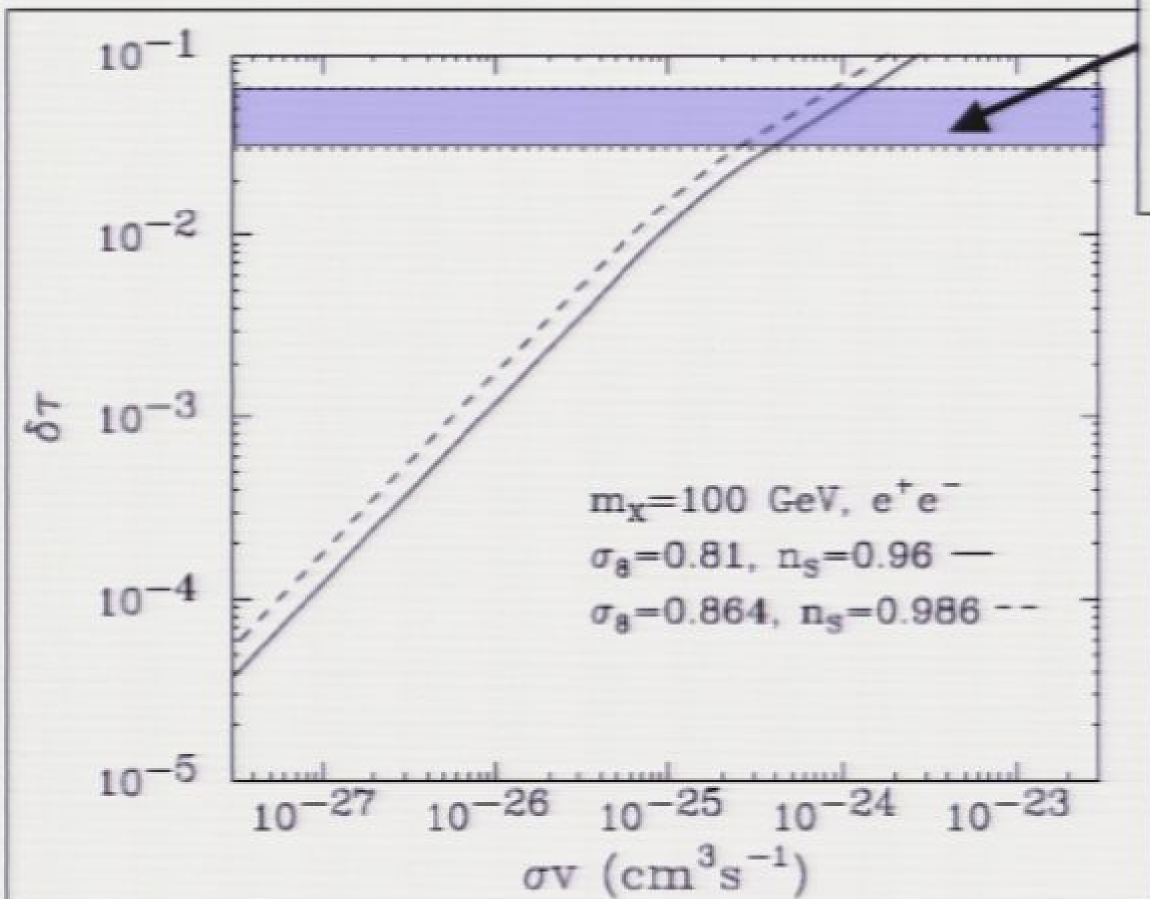
Did Dark Matter Reionize Our Universe?



Observed degree of reionization (z>6)
(WMAP optical depth)

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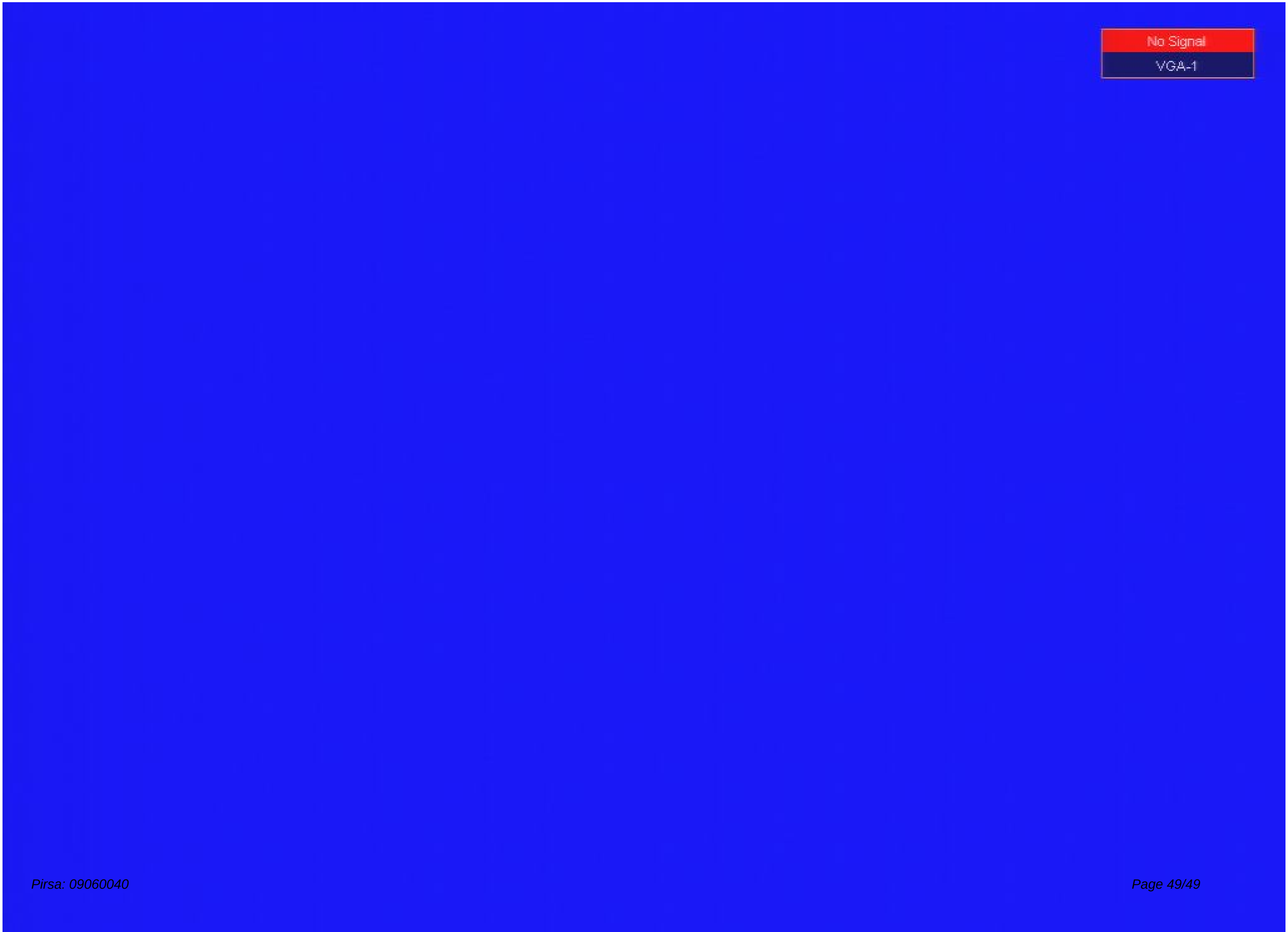
Belikov and Hooper, arXiv:0904.1210


No Signal
VGA-1